[RHIC/JLab] to EIC
Connections & Complementarities

Abhay Deshpande
Stony Brook University & RBRC

- This talk is **NOT** intended to make the case for the EIC

- It is an *attempt* only to bring out the highlights of complimentarity and connectedness amongst probes for understanding QCD

Layout of this talk

- Complimentary tools & methods of high energy physics, some concrete examples…

- Open questions in QCD
  – Limitations of present experimental tools
- Science goals of EIC:
  – Define the machine parameters
  – Golden measurements… what will we learn?

- EIC Realization: (only in comments, no slides)

QCD

Folks, we need to stop "testing" QCD and start "understanding" it

Yuri Dokshitzer

1998, ICHEP Vancouver, CA in his Summary Talk

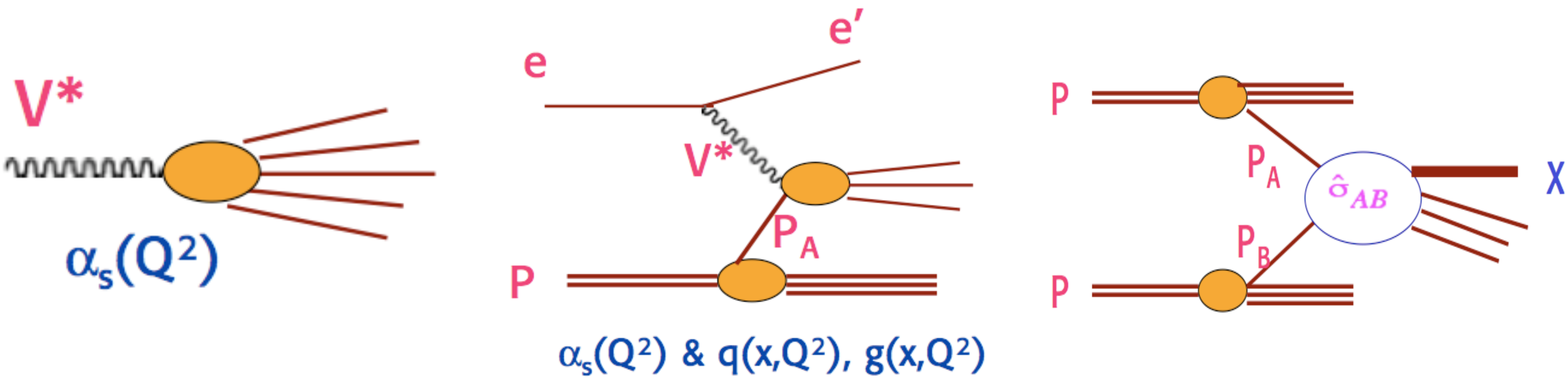
2004 For the discovery of asymptotic freedom in QCD

While there is no reason to doubt QCD any more, our level of understanding of QCD remains extremely unsatisfactory

What tools do we have to study QCD?

Experimental tools of (particle) physics

Collisions of e-e, e-p and p-p scattering



Progress in our understanding of nature needs continuous interplay amongst different tools…

Only by doing that can we make full use of their diversity & complementary

G. Altarelli, DIS09

Interplay e-e, p-p in High Energy Physics

SLAC, Tevatron, HERA, LEP… recently other lower energy e-e (KEK, SLAC) for precision studies

In fact, presently the high energy physics community is planning their future in a particular sequence:

First a p-p (LHC) collider will explore physics at high energy

Then an e-e (ILC) collider energy will be chosen to precisely measure the physics of most interesting region

A case of explicit dependence and connection between pp and ee machines

Also relevant to us in (QCD studies):

Detailed study of QCD (I) : e-e, e-p and p-p

- Add Spin
  - **Spin allows precision**: Weinberg angle from SLC 25 times more precise with *polarized* beams
  - **Spin is full of surprises**: Spin Crisis, transverse spin phenomena

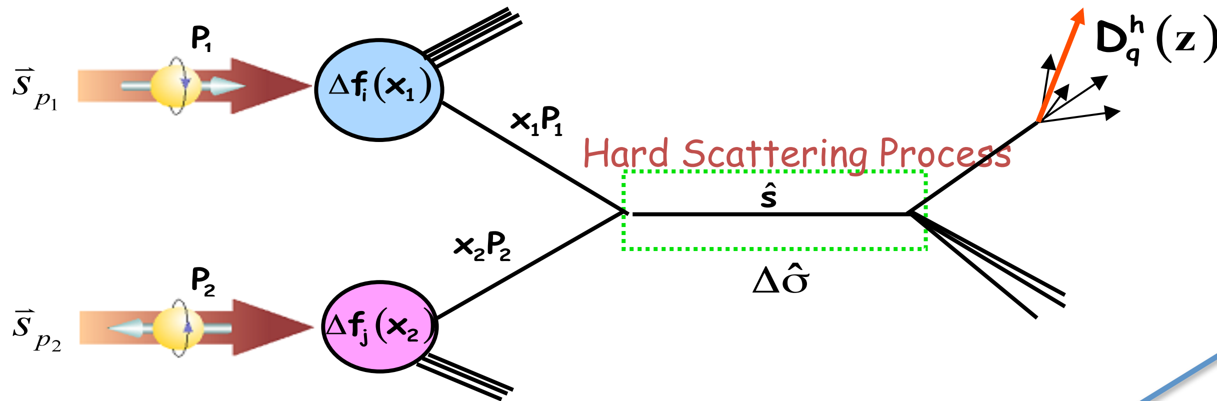
A Detailed study of QCD (II): d-A, e-A

- Add Nuclei, highly dense objects (nature's gift!)
  - Detailed study of glue → In itself interesting
  - Nuclear PDFs (initial state) to understand the evolution of initial state to final, of A-A collisions at high energy

Sassot's talk today

Examples of interplay between ee, ep and pp, along with theory in nucleon spin…. Recent interests

Measurement of ΔG at RHIC

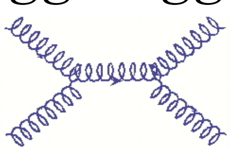


Taneja & Wissink

- Determination of ΔG involves input from DIS, pQCD & ee

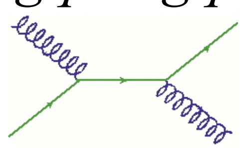
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{\pi/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{\pi/c}}$$

$gg \rightarrow gg$



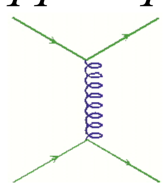
$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$

$gq \rightarrow gq$

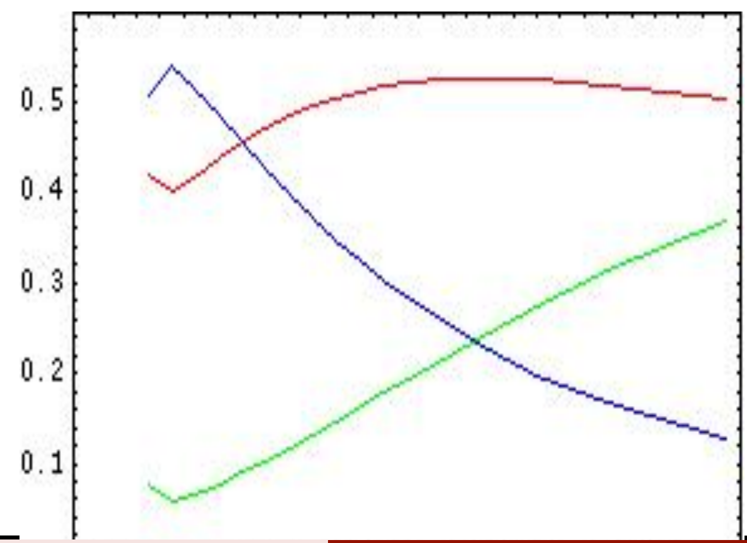


$\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$

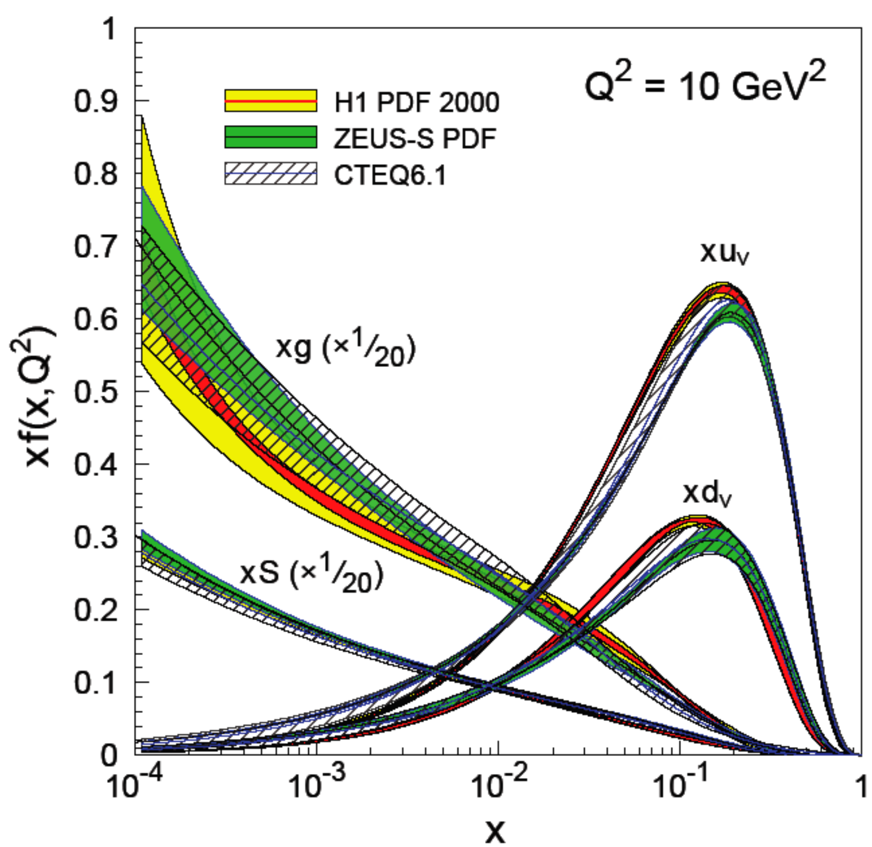
$qq \rightarrow qq$



$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$



Low x spin ΔG measurements



- RHIC p-p measures: ΔG/G
  - G is very large at low x
- ΔG/G measurement at low x "unfairly" difficult
- A_1, g_1 (from DIS) → ΔQ/Q
  - Evolution in Q^2
- Life relatively easier?

Transverse spin phenomena clearly related to the partonic processes before (Sivers), after collisions (Collins Fragmentation)

The Challenge:

Can we unfold them convincingly?

Belle, HERMES/COMPASS & RHIC data will play a role!

Theory talks by Anselmino, Metz, Feng
Experimental talks by
Koster, Fersch, Peng, Liu, Seidl, Hasch, Dunnen

The interplay between ee, ep and pp ....

To see if we understand SSA completely: ee, ep, pp essential!

Example:

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to \pi^{+}X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot G(x_2) \times \boxed{\frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2}} \times FF_{q_{k,l}}(z, p_{h,T})$$

SSA in pp

Proton structure (ep)

Theory input

Fragmentation (ee)

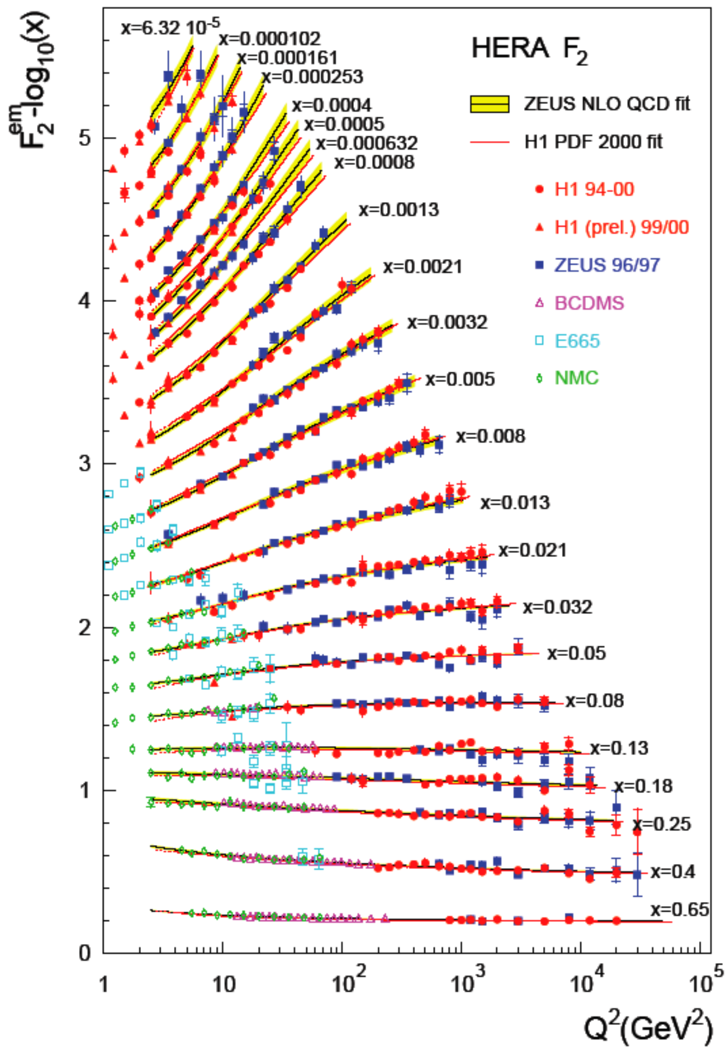
- Another view (***<u>not</u>*** at odds with the previous):
  - ep, ee experiments measure objects
  - Theorists use them and (**techniques + assumptions**) in (p)QCD to calculate/predict outcomes in pp scattering
  - pp experiments the ideal **(the only)** place **<u>to test our understanding of QCD</u>**

…. That was: the complementarity of *tools* of study in QCD and some of their relative strengths…

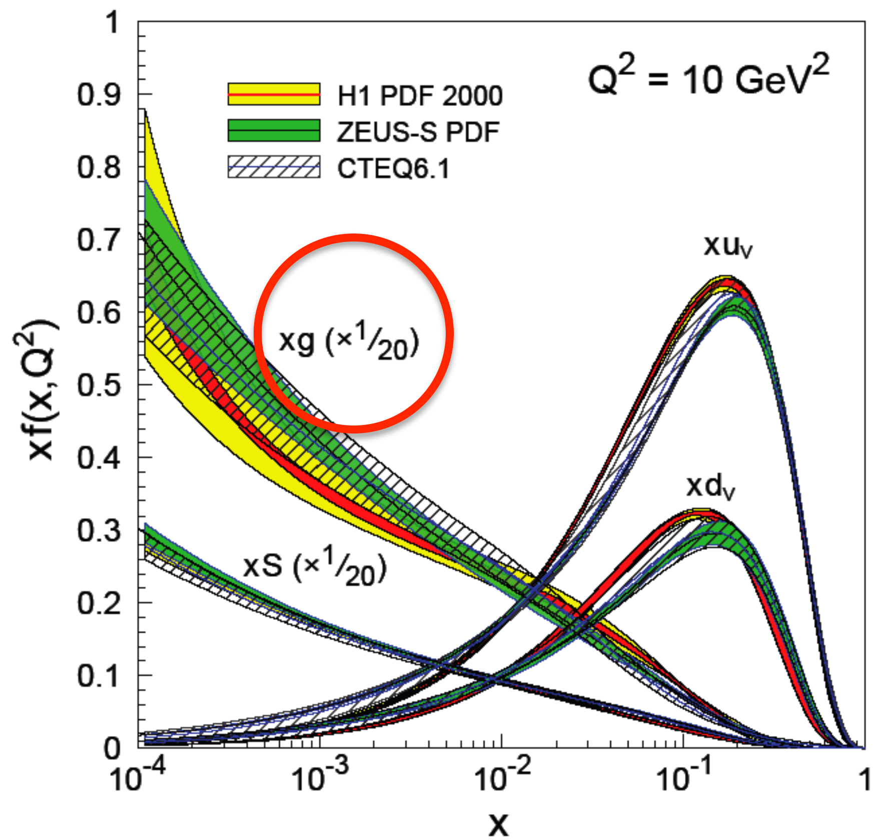
…. Now lets consider some complementarity in measurements between present experiments and the future EIC.

Some puzzles & open questions in QCD:

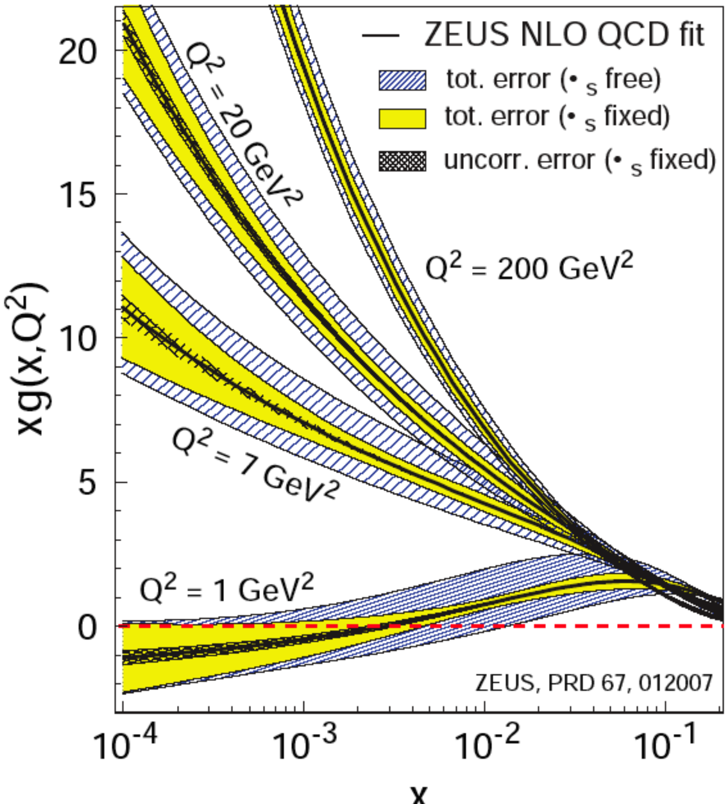
Measurements of Glue at HERA



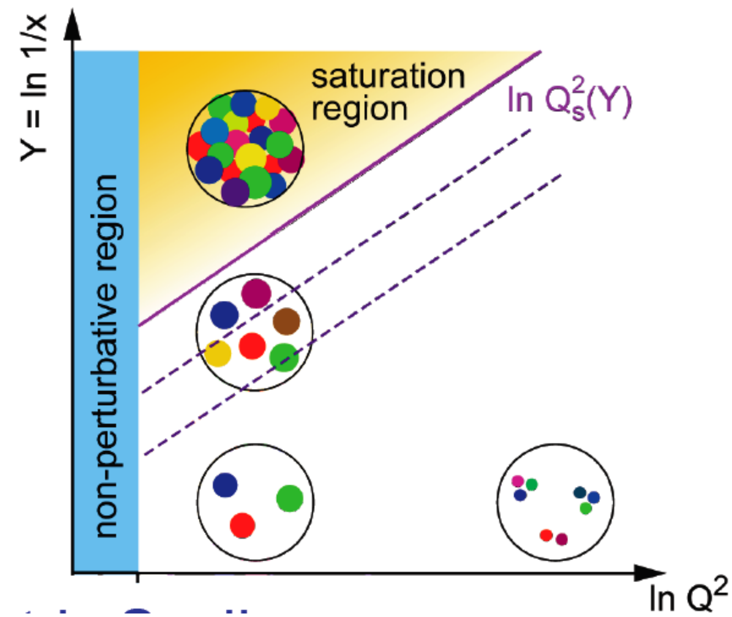
- Scaling violations of $F_2(x,Q^2)$
- NLO pQCD analyses: fits with **LINEAR** DGLAP equations



Gluons still not well understood!



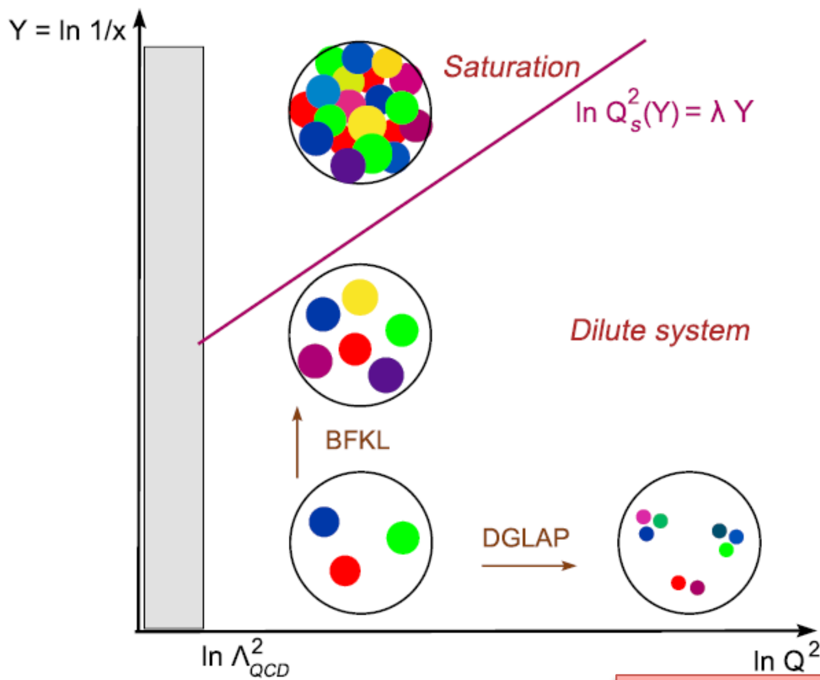
- Rise at high Q^2, low x
  - Infinite rise, infinite cross section?
  - Is this due to use of **linear** DGLAP?
  - Direct consequence to high energy hadron cross sections
- Negative g(x) at low Q^2?



- What is the effect of including **non-linear** effects in DGLAP equation?
  - BK, JIMWLK
- A possible scenario: Color Glass Condensate
- Characteristic scale $Q_s(x,A)$
- Experiment with high densities of gluons → Nuclei!

Color Glass Condensate

Recent Review: F. Gelis et al., , arXiv:1002.0333



gluon density $n(Y,k_T)$ saturates for large densities at small x :

Non-linear evolution eqn.

$$\frac{\partial n}{\partial Y} \cong \underbrace{\lambda\alpha_S n}_{\text{g emission}} + \underset{\uparrow\,\text{diffusion}}{\nu\alpha_S \partial_t^2 n} - \underbrace{\mu\alpha_S^2 n^2}_{\text{g-g merging}}$$

$$\alpha_S n \propto 1$$

In this meeting:
Theory Dumitru, Jalilian-Marian
Experiment: Citron, Crawford

Saturation Scale Q_s; Nuclear oomph factor $A^{1/3}$
RHIC d-A program: measurement possible, …
G(x) measurement for different A(?)
Why not use Nuclear DIS at high energy?

How well do we understand the nucleon spin?

If you think you understand hadronic reactions,
try to explain them with spin

Experiments with spin have managed to kill
more theories and models than any other single
variable used in experiments

Nucleon Spin ~~Crisis~~ Puzzle

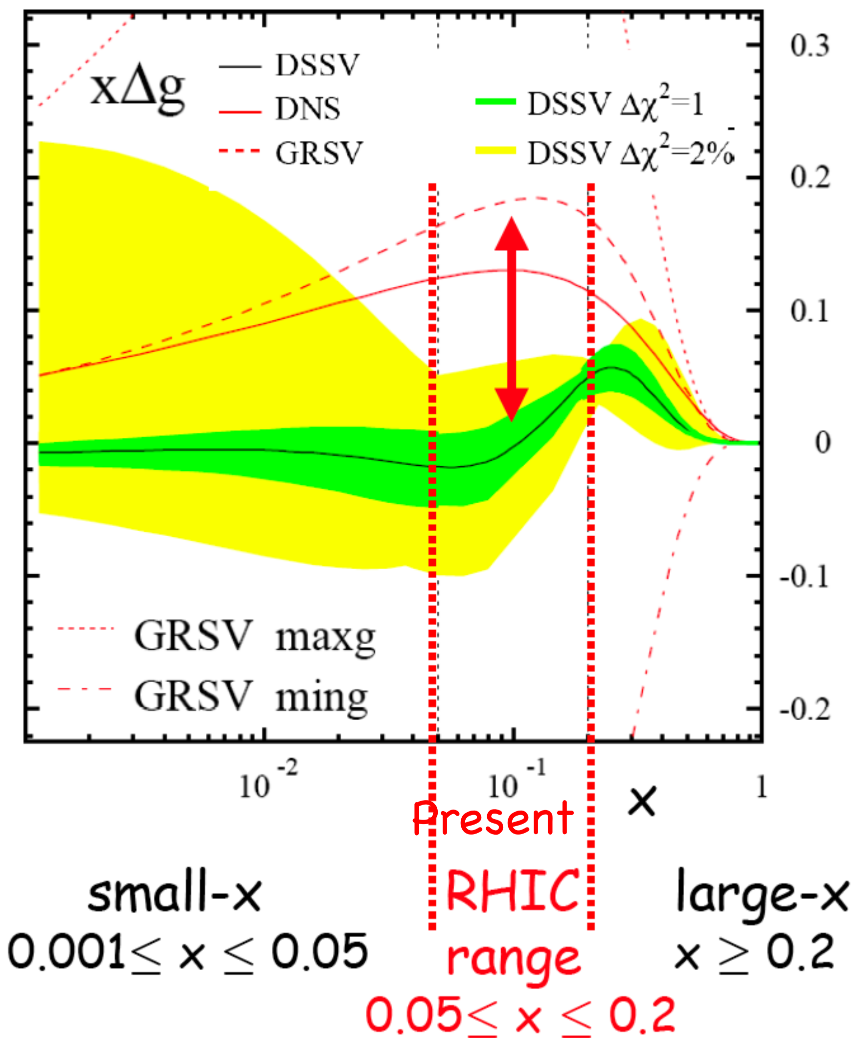
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_Q + \Delta G + L_G \qquad (?)$$

- We know how to measure $\Delta\Sigma$ and ΔG precisely using pQCD in a model independent way
  - ½ ($\Delta\Sigma$) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: ΔG *not large* as anticipated in the 1990s, but *measurements incomplete, precision at low x?*
- Orbital angular momenta: L_Q (L_G?)

Z.E. Meziani's talk

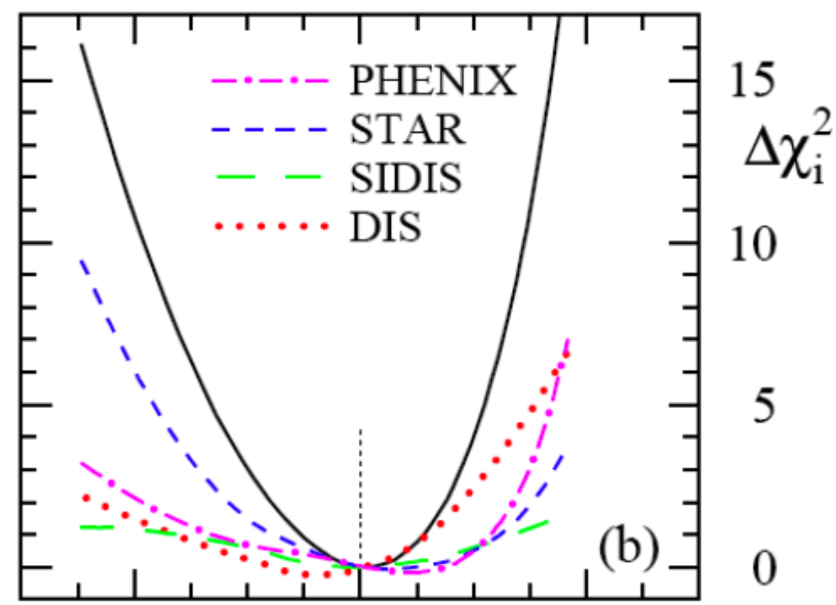
  - Through **GPDs:** 3D tomographic images of the proton
  - Significant model dependence…
  - A lot to learn from the 6 GeV and the 12 GeV Jlab program & an ongoing theoretical development

ΔG(x) @ Q^2=10 GeV^2



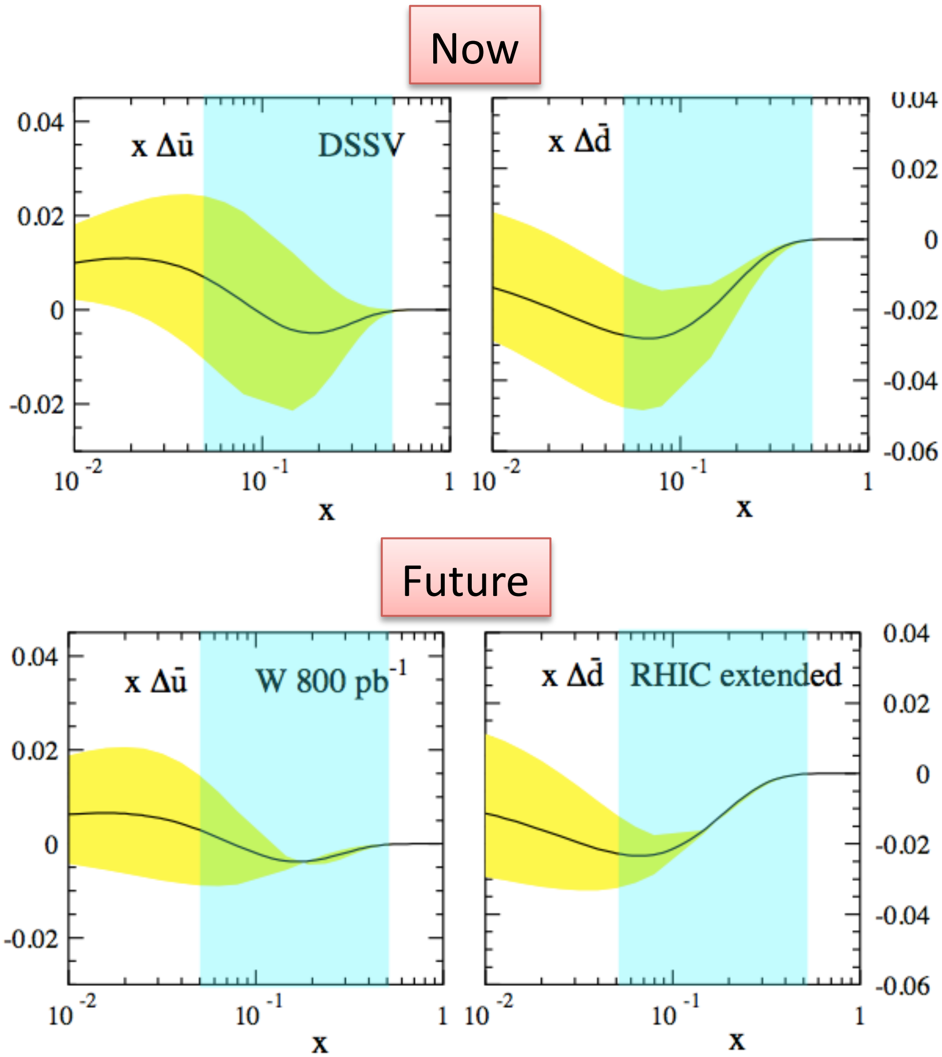
De Florian, Sassot, Stratmann & Vogelsang

- **Global analysis: DIS, SIDIS, RHIC-Spin**
- **Uncertainly on ΔG large at low x**



$$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10\ \mathrm{GeV}^2)\,dx$$

Anti-Quark Distributions



D. DeFlorian, this meeting, 3/16/2010

- Although RHIC Data will allow an independent and important avenue to determine anti-quark pdfs, the low x will remain unexplored.
- *A future machine needs to be able to access this.*

Measurement of GPDs via DVCS, DVVM

Hasch

- Extensively measurements by HERMES and now by JLab & COMPASS experiments
  - Limited kinematics
  - Mostly access quark GPDs
  - Detailed program on going planned at JLab12

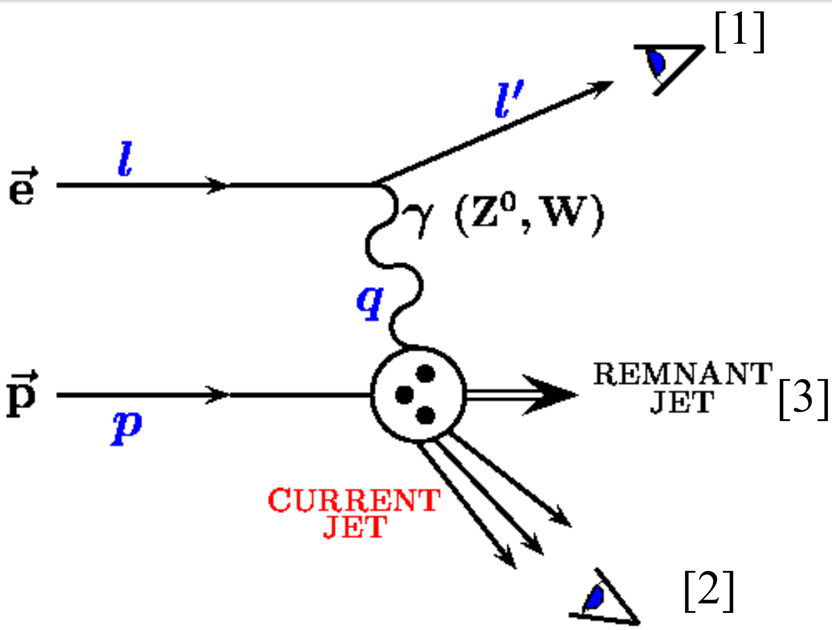
Z-E Meziani

- Accessibility to gluon GPDs very limited: *An emergent consensus that a future higher energy collider would be needed to fully measure the GPDs*

The EIC Proposal

- A high energy, high luminosity (polarized) ep and eA collider and a suitably designed detector to address some of the most fundamental questions in QCD
  - High Energy → low x, high Q^2 accessibility
  - High luminosity → Rare processes, spatial distributions of partons in nucleons
  - Nuclei → gluon dominated, study of nuclear PDFs
  - Polarized → spin structure of nucleons

Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p\cdot q}$$

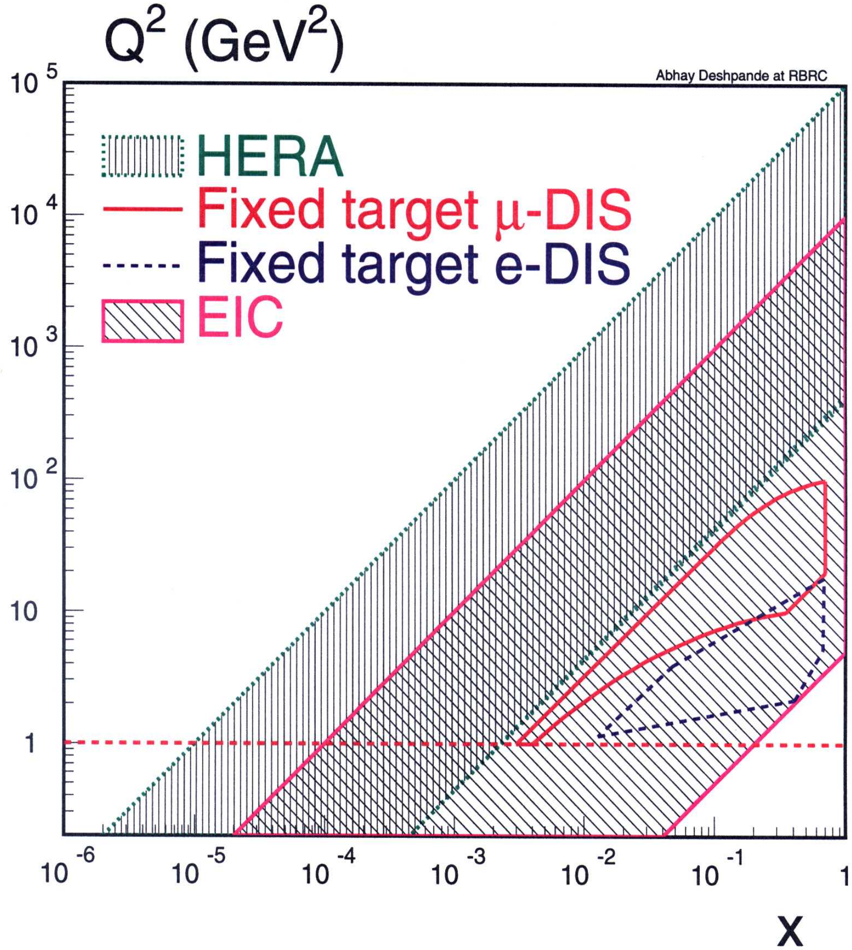
$$y = \frac{p\cdot q}{p\cdot l}$$

$$s = 4E_e E_p$$

$$W = (q+p)^2$$

- Inclusive [1], semi-inclusive [1,3], exclusive [1,2,3]
- Luminosity requirements lowest [1] → highest [1,2,3]
- Exclusive measurements: demanding requirements on the detector design and its integration with the machine lattice

EIC in the US: Basic Parameters



- E_e=10 GeV (5-20 GeV variable)
- E_p=250 GeV (50-250 GeV Variable)
- Sqrt(S_{ep}) = 30-100 GeV
- $X_{min} = 10^{-4}$; $Q^2_{max} = 10^4$ GeV
- Beam polarization ~ 70% for e,p
- Luminosity $L_{ep} = 10^{33\text{-}34}\ cm^{-2}s^{-1}$
- Aimed Integrated luminosity:
  - 50 fb^{-1} in 10 yrs (100 x HERA)
  - Possible with $10^{33}\ cm^{-2}s^{-1}$

Nuclei:

- **p->U; E_A=20-100 GeV**
- **Sqrt(S_{eA}) = 12-63 GeV**
- **$L_{eA}/N = 10^{33}\ cm^{-2}s^{-1}$**

Overarching goals of EIC

- **Nucleon Spin Structure**
  - **Longitudinal spin structure: ΔG, ΔQ, ΔQbar**
    - ***Mostly inclusive & semi-inclusive measurements***
  - **Nucleon spatial structure**
    - **TMDs & GPDs (→L_z?)**
    - ***Mostly semi-inclusive & exclusive measurements***

- **QCD at extreme condition & spatial structure of nuclei**
  - **Low x gluon distribution & GPDs in nuclei**
  - ***Inclusive & semi-inclusive (diffractive & other) off nuclei***

- Parity & Precision EW Physics (Emergent ?)
  - *Inclusive, semi-inclusive/exclusive physics*

EIC Data & its impact: Complementary with existing kinematic regions....

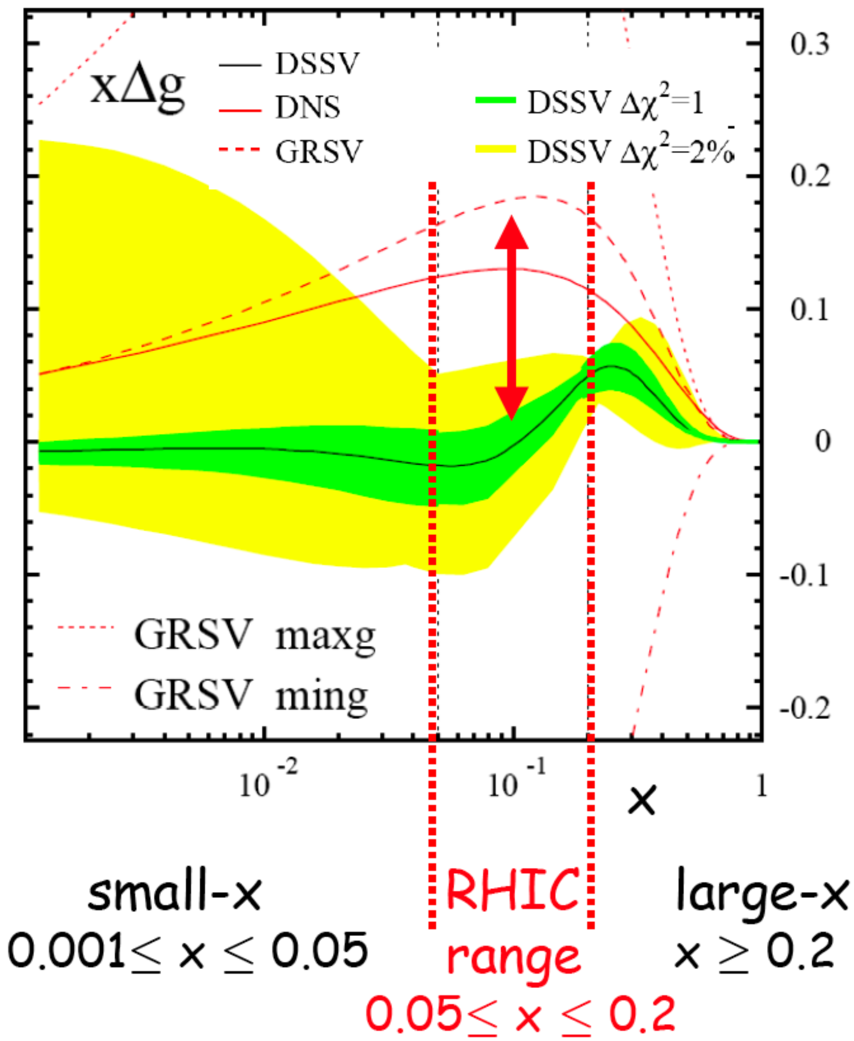
Type [1]: Inclusive DIS: L_{ep} ~ 2 fb^{-1}

Type [1,3]: Semi-Inclusive DIS: L_{ep} ~ 4-10 fb^{-1}

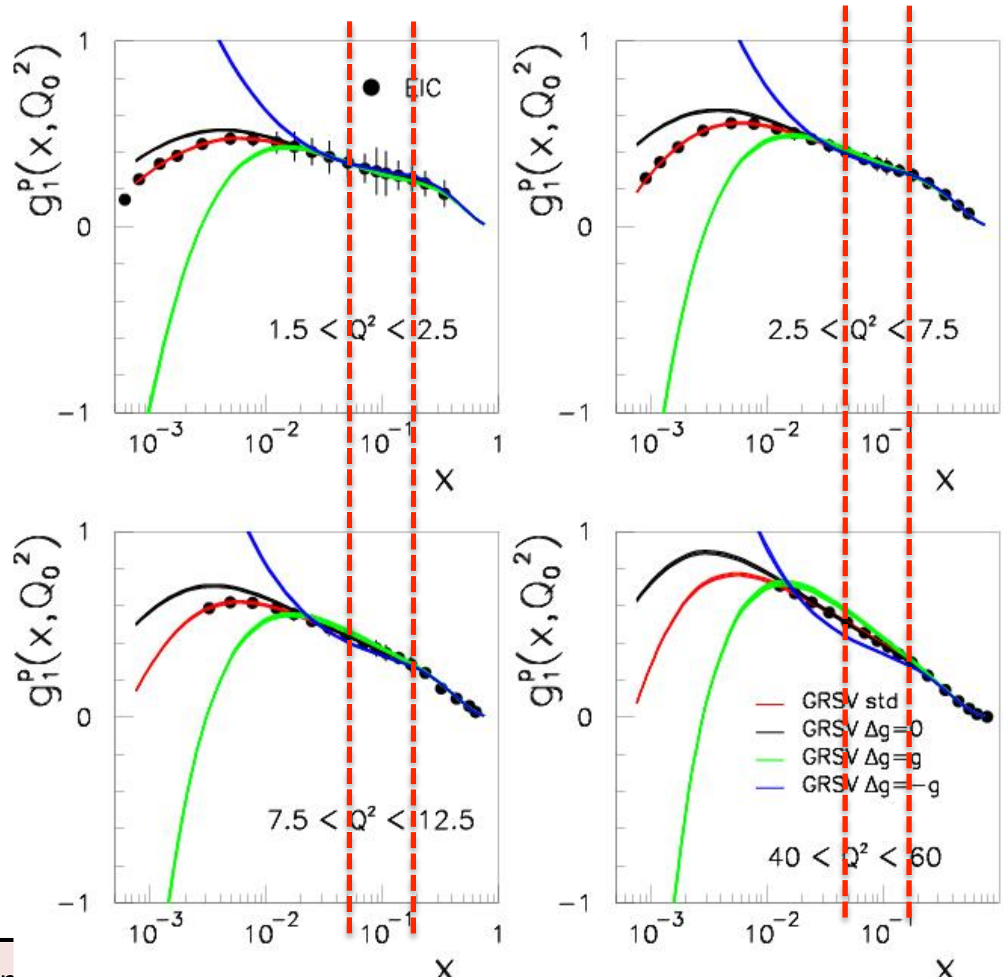
Type [1,2,3]: Exclusive DIS: L_{ep} ~ > 10 fb^{-1}

Detector requirements & its integration with machine lattice most demanding for EIC, and in particular, for the Exclusive Measurements

Precision measurement of ΔG

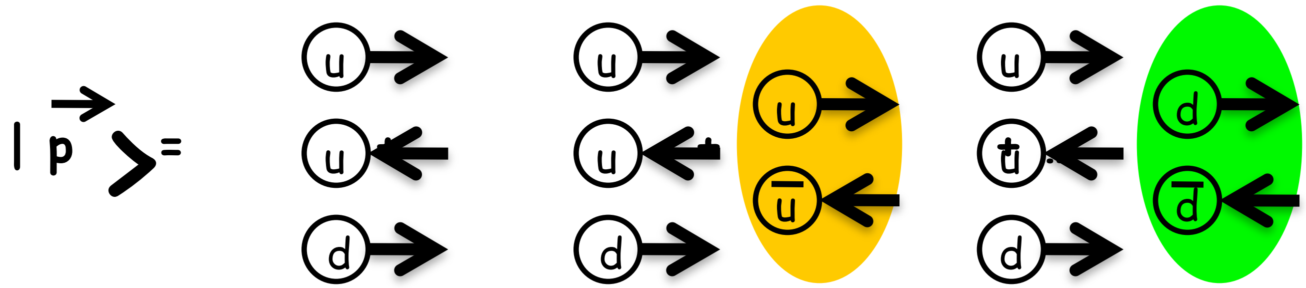


- Different $g_1(x,Q^2)$ curves for different ΔG values



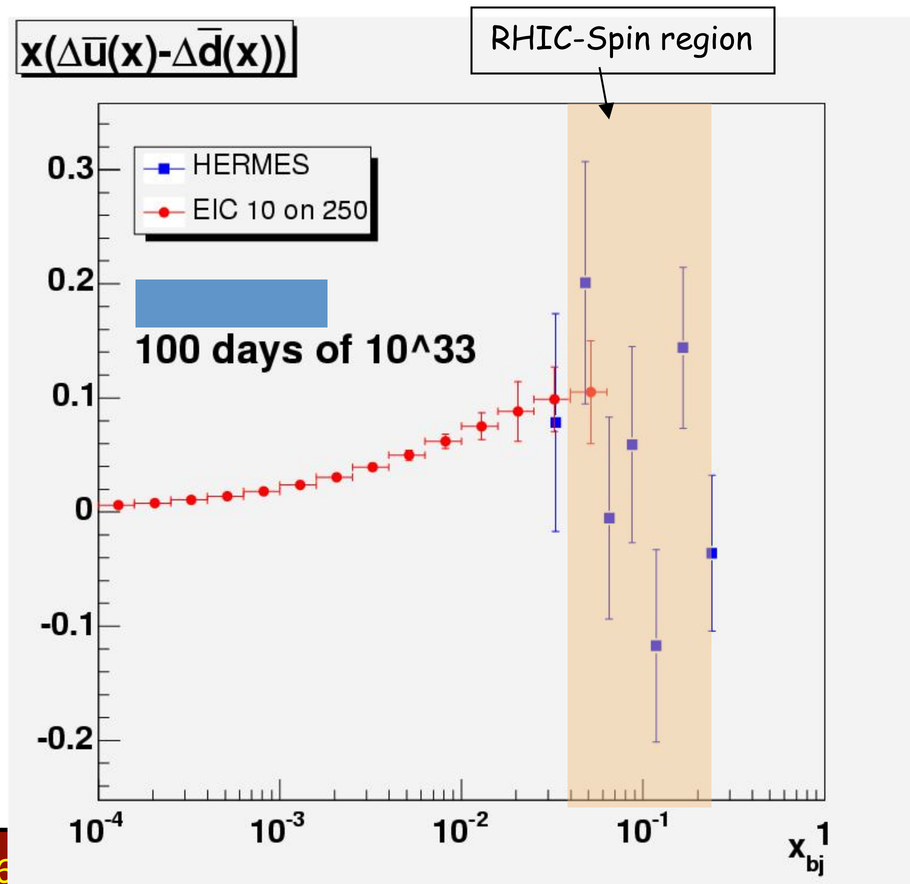
Precisely image the sea quarks

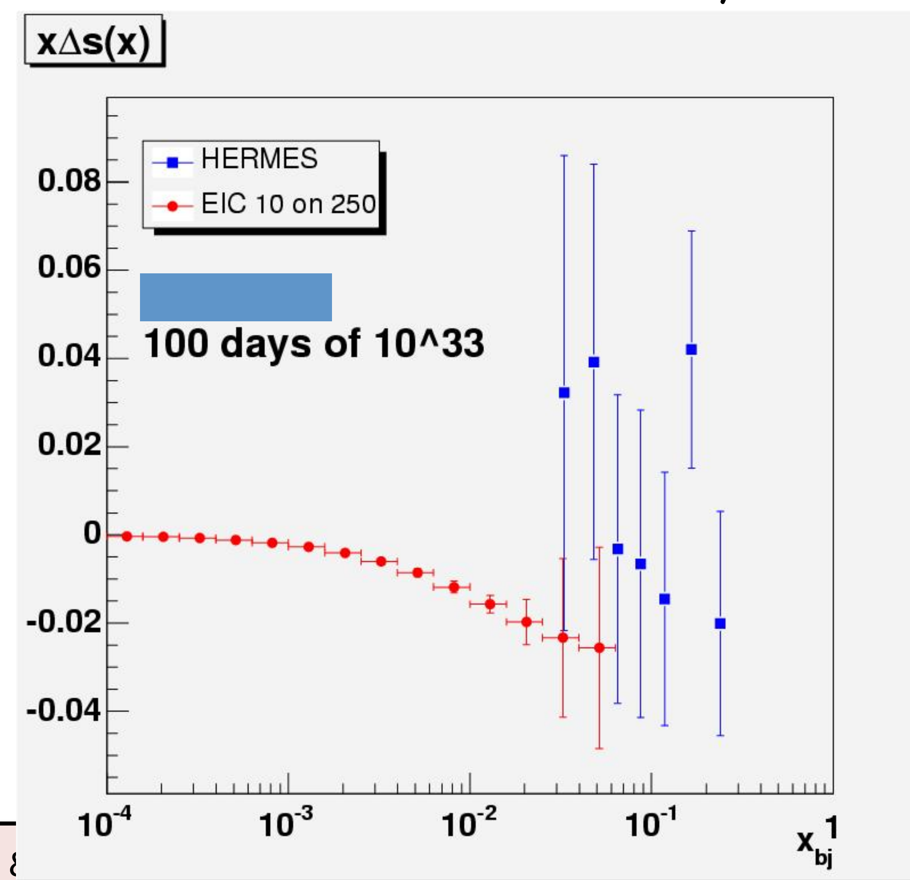
Spin-Flavor Decomposition of the Light Quark Sea



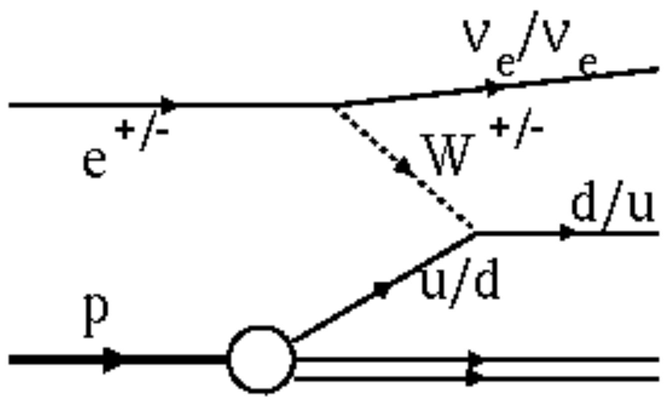
Many models predict

$\Delta\bar{u} > 0,\ \Delta\bar{d} < 0$





Parity Violating Structure Function g_5



$$\frac{d^2\sigma}{dx\,dQ^2} \sim \left\{a\left[F_1 - \lambda b F_3\right] + \delta\left[a g_5 - \lambda^2 b g_1\right]\right\}\frac{1}{(Q^2+M_W^2)^2}$$

where

$a = 2(y^2 - 2y + 2)$; $\quad b = y(2-y)$; $\quad \lambda = \pm 1$ for $e^{\pm}$

$\delta = \pm 1$ for $\uparrow\downarrow$ and $\uparrow\uparrow$ spin orientations

- Experimental signature is a huge asymmetry in detector (neutrino)
- Unique measurement
- Unpolarized xF_3 measurements at HERA in progress
- Will access polarization of heavy quarks/anti-quarks

$$A_{cc}^{W^+} = \frac{-2bg_1 + ag_5}{aF_1 - bF_3} \qquad A_{cc}^{W^-} = \frac{+2bg_1 + ag_5}{aF_1 + bF_3}$$

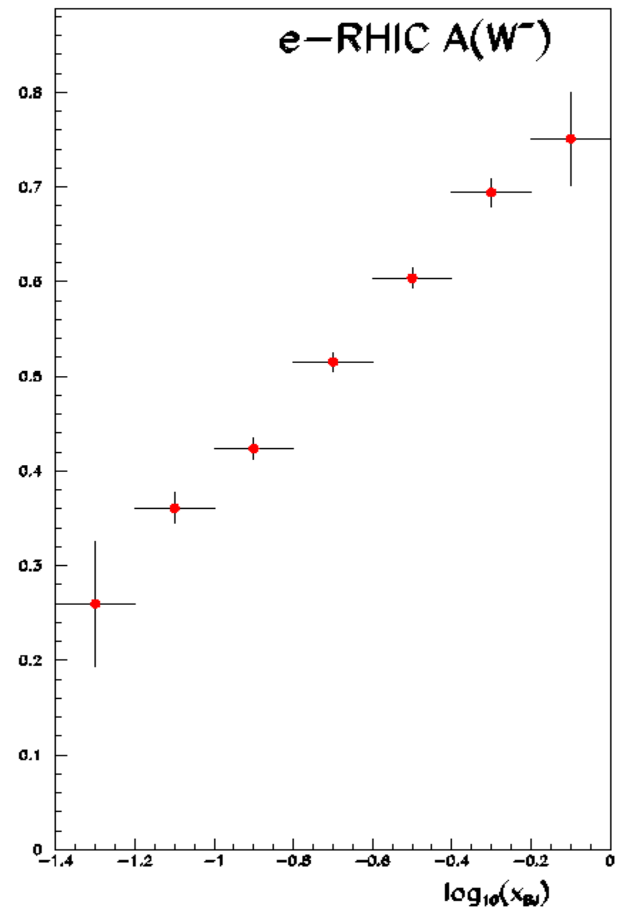
For eRHIC kinematics $a \gg b$

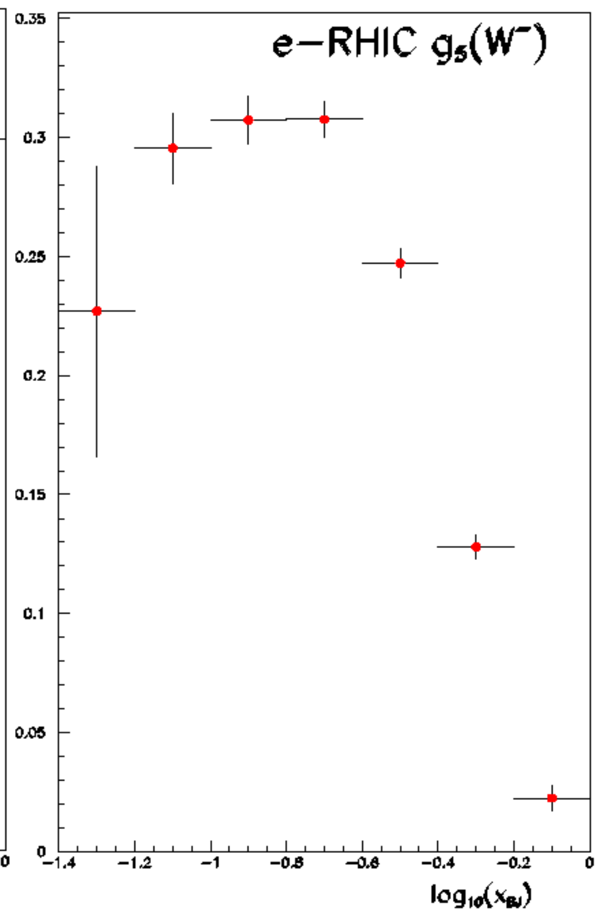
$\Rightarrow g_5$ dominates $\rightarrow$ Extract g_5

$$g_5^{W^-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$$
$$g_5^{W^+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}$$

Need electron and positron beams in the EIC

Measurement Accuracy PV g_5 with EIC





Assumes:

1. Input GS Pol. PDFs
2. xF_3 measured by then
3. 4 fb^{-1} luminosity

Positrons & Electrons in EIC
➔ $g_5(+)$ & $g_5(-)$

>> One reason for keeping the option of positrons in the EIC

>> For LINAC-Ring eRHIC, enormous effort on intense enough positron source R&D needed.

Type [1,2,3]: Exclusive DIS

Luminosity Requirement: ~ >10 fb^{-1}

Good EM, Hadron calorimetry

Good particle ID

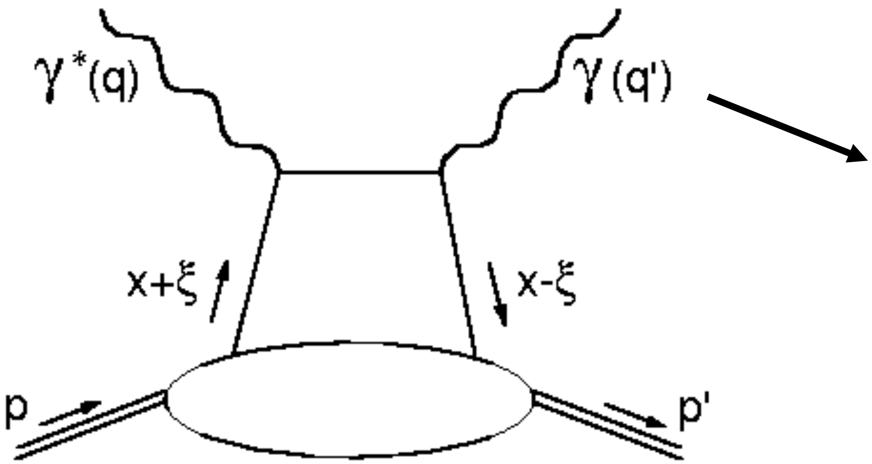
4π coverage of detector

Operation in high rate environments

Recall: 10^{33} $cm^{-2}s^{-1}$ → 5 fb^{-1} in 10 weeks

With 70% detector & 70% machine efficiency

DVCS/Vector Meson Production



- Hard Exclusive DIS process
- γ (default) but also vector mesons possible
- Remove a parton & put another back in!

- Access to Generalized Parton Distributions with theoretically clean connections to partonic orbital angular momentum!

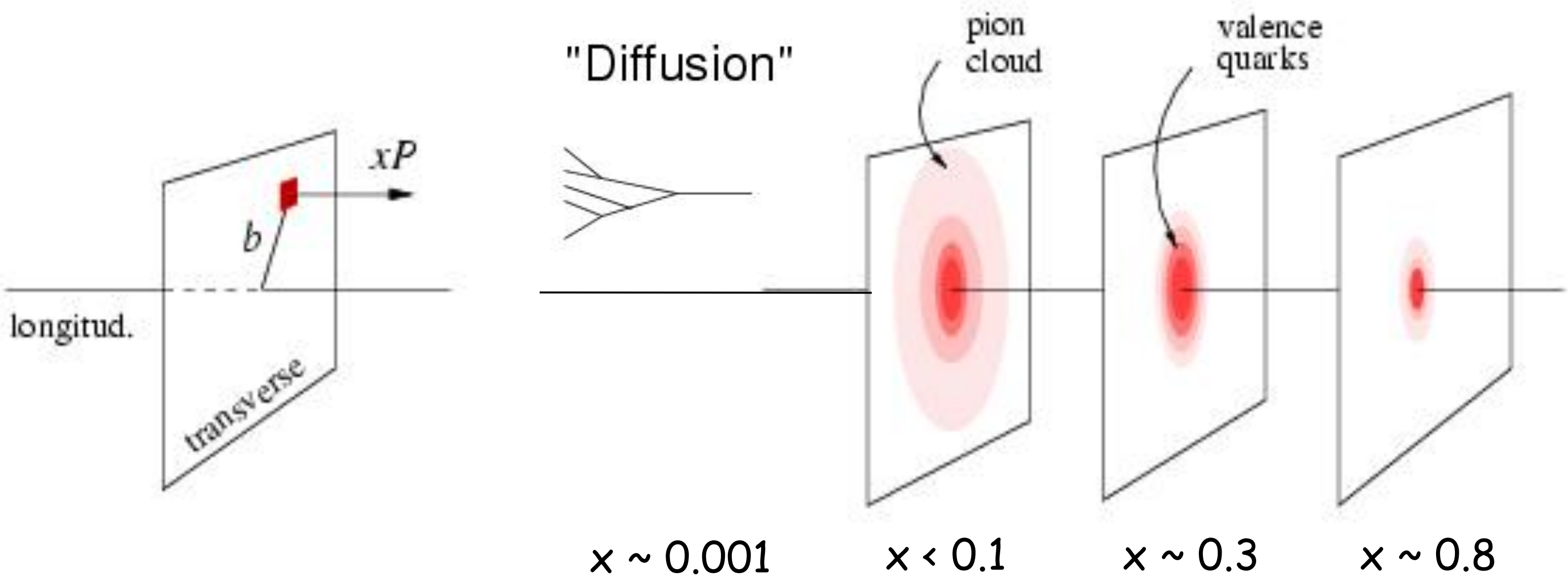
$$\int x dx [H(x, \underset{\downarrow}{t}, \xi) + E(x, \underset{\downarrow}{t}, \xi)] = 2J_{quark} = \Sigma + 2L_q$$

0   0 --> $-Q^2$

Experimental effort just beginning…To fully explore this physics **beam Charge asymmetries need** to be measured… **=> Luminosity Hungry Measurement**

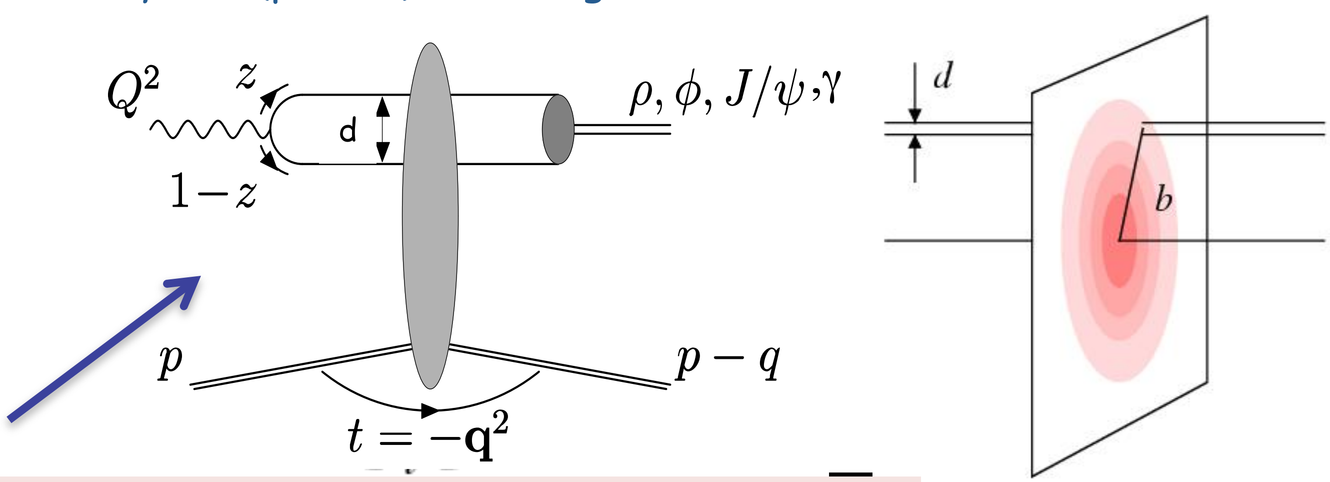
GPDs and transverse parton imaging

Fourier transform in momentum transfer



gives transverse size of quark (parton) with longitud. momentum fraction *x*

EIC:
1) x < 0.1: gluons!
2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.

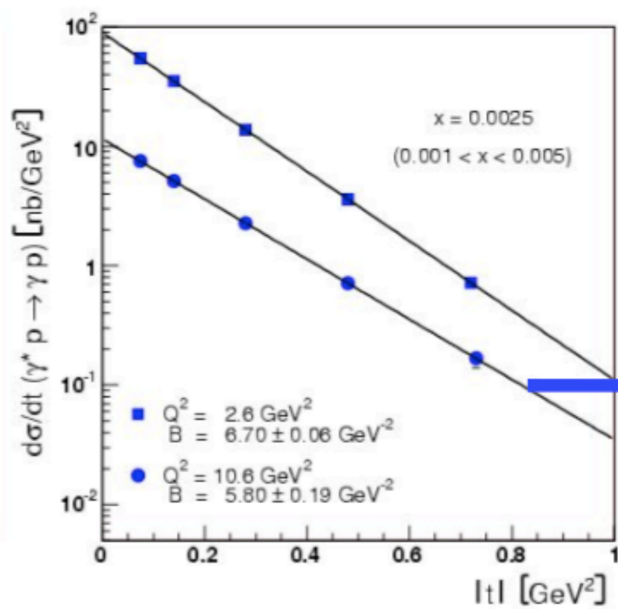


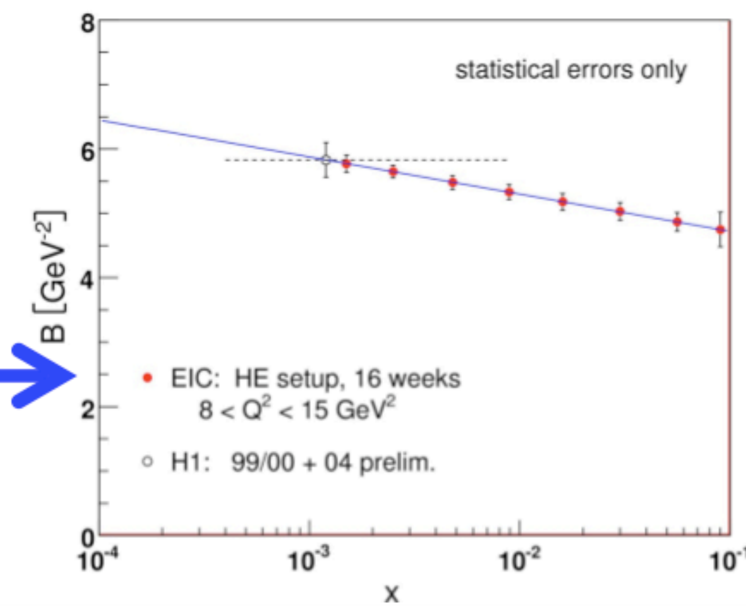
GPDs & Transverse Gluon Imaging

DVCS/DVVM Measurements require

- A wide x-range $0.001 < x < 0.1$ (lower the x larger the glue)
- A large Q^2 & wide range: 10-20 GeV^2 for clear interpretation
- Sufficient luminosity to study Q^2, W^2 & t dependence of cross section

EIC Simulations for 10 x 250 eRHIC design with real RHIC Lattice @ $L_{ep}=10^{33}$ $cm^{-2}s^{-1}$





Study of Glue facilitated by e-<u>**A**</u>?

- An e-p collider at high energy: HERA (1992-2006)
  - No unambiguous evidence of non-linear QCD effects

- eA at the EIC: will probes interactions over distances L ~1/(2m_Nx)
  - For L > 2R_A ~$A^{(1/3)}$ probe interacts coherently with all nucleons in the nucleus
    - Hence nuclear enhancement $$\boxed{(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}}$$

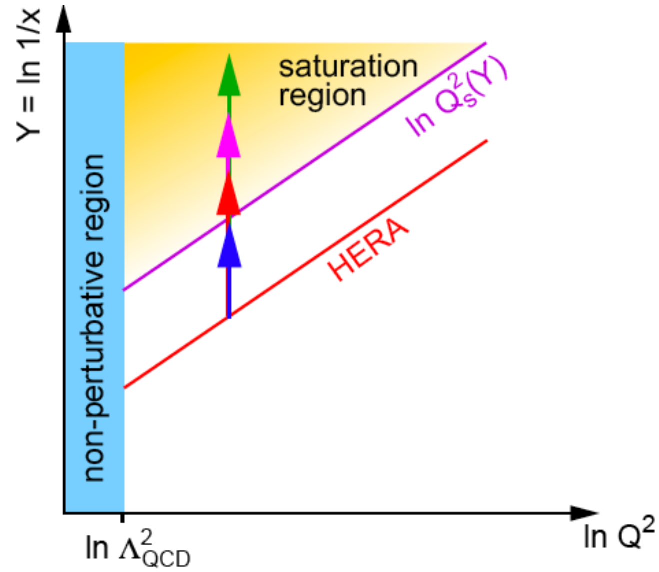
Kowalsky & Teany PRD 68:114005 ==> b & x dependence of Q_s from diffractive and exclusive measurements at HERA

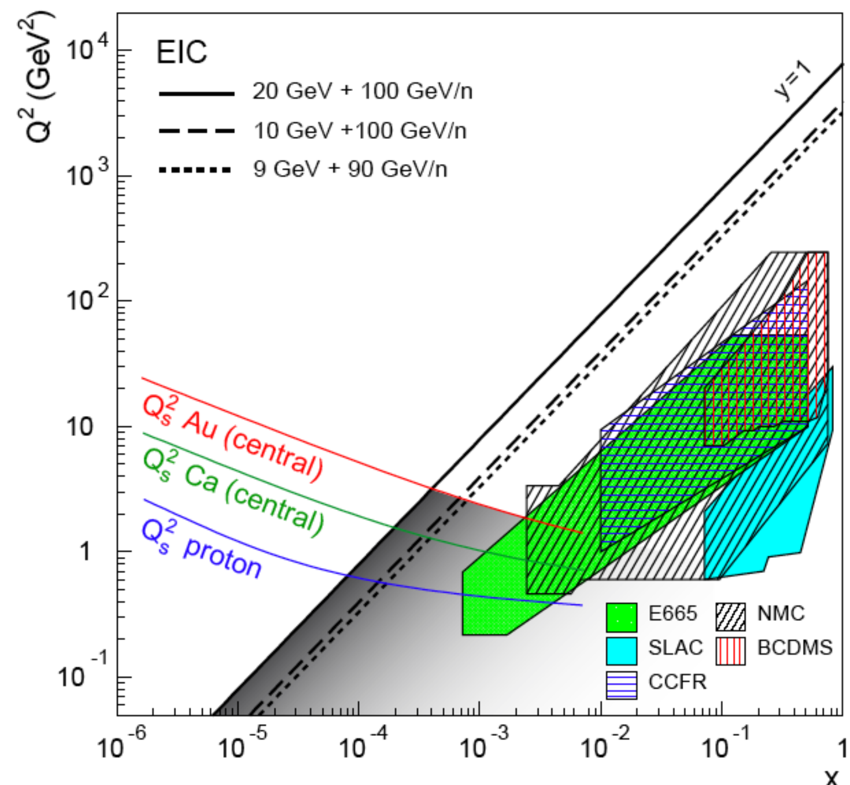
  - Enhancement of Q_s with A ==> non-linear QCD regime at significantly higher x (I.e. lower CM) in A than in a proton!
  - This enhancement is crucial for making the case for i.e. selecting proper values for beam energies and nuclei for eA@RHIC

eA physics drives e-beam energy!

EIC Beam Energy (GeV)	√s (GeV)	low-x reach compared to HERA (e+p equivalent)
2+100	28	4
10+100	63	18
20+100	89	36
20+130	102	50
30+130	125	71

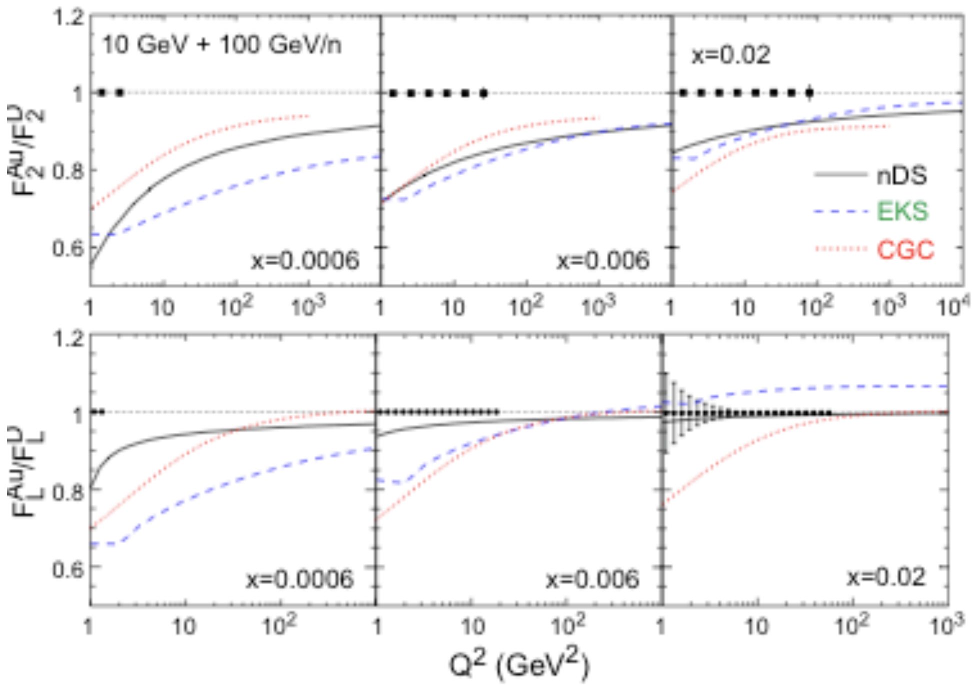
- We do not know for sure where saturation will be seen
- What is a safe margin over HERA?
  - A 50-100 times improvement may be desired



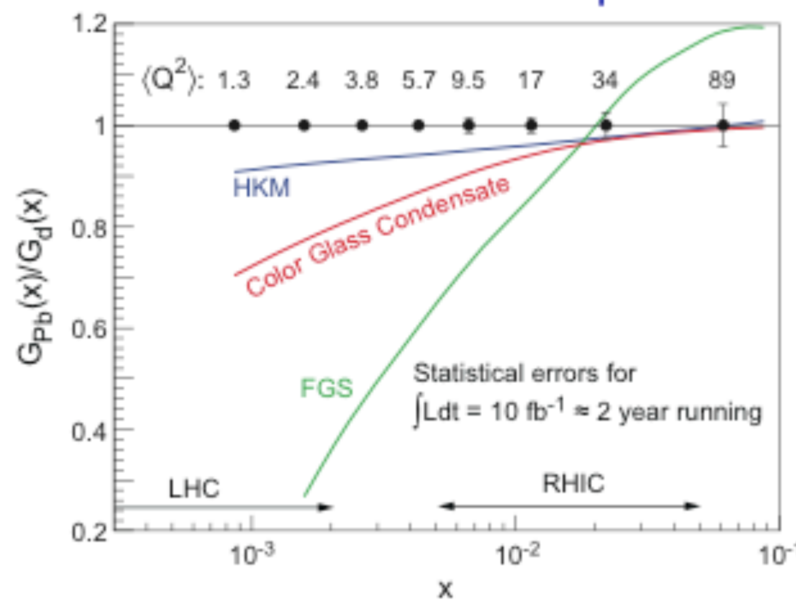


Early e-A simulations

Simulations to demonstrate the quality of EIC measurements



Folded with EIC acceptance



$F_L \sim \alpha_s\, G(x,Q^2)$ requires $\sqrt{s}$ scan, $Q^2/xs = y$

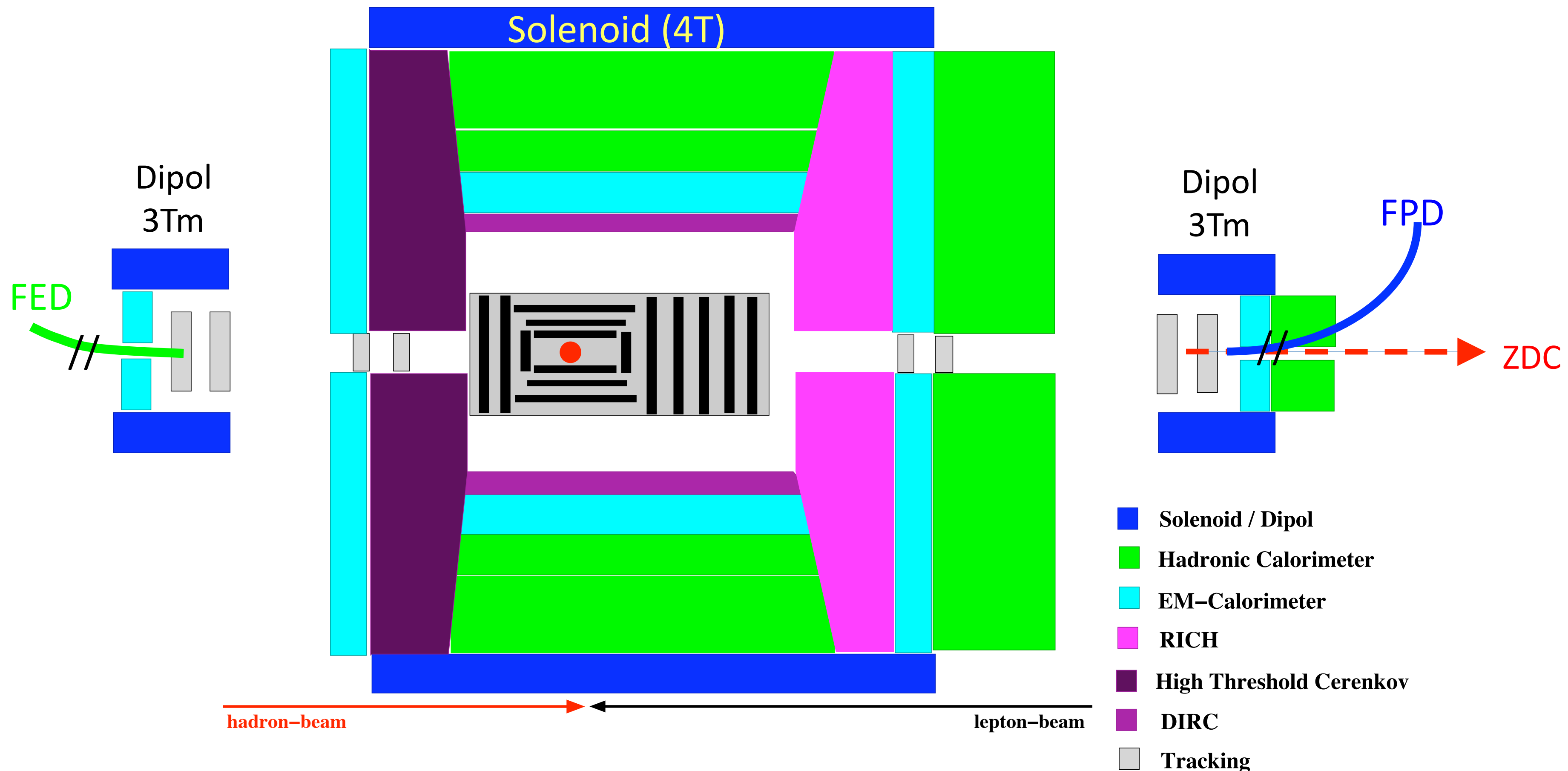
Assume:
L = $3.8\ 10^{33}$ cm^{-2} s^{-1} (100x Hera)
T = 10 weeks
duty cycle: 50%
L ~ 1/A (approx)
$\int Ldt$ = 11 fb^{-1}

Plots above:
$\int \mathcal{L}dt$ = 4/A fb^{-1} (10+100) GeV
= 4/A fb^{-1} (10+50) GeV
= 2/A fb^{-1} (5+50) GeV
statistical error only

I have shown you many plots of what EIC could do…. But details of detector simulations, IR design and its integration are yet to be done.

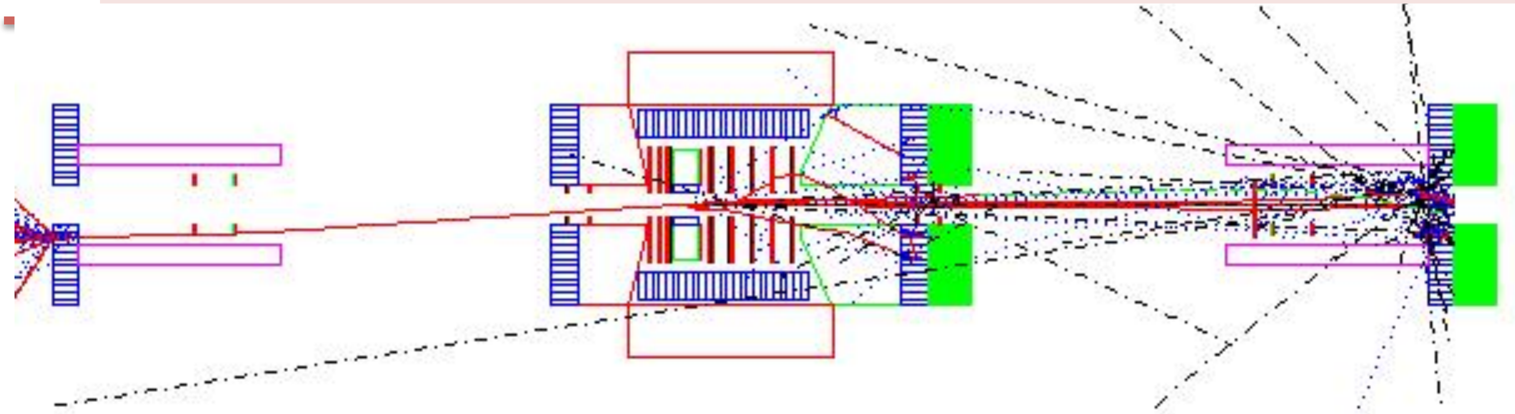
That kind of effort is just beginning through many workshops, meetings and working groups/ task forces setup at the two Labs.

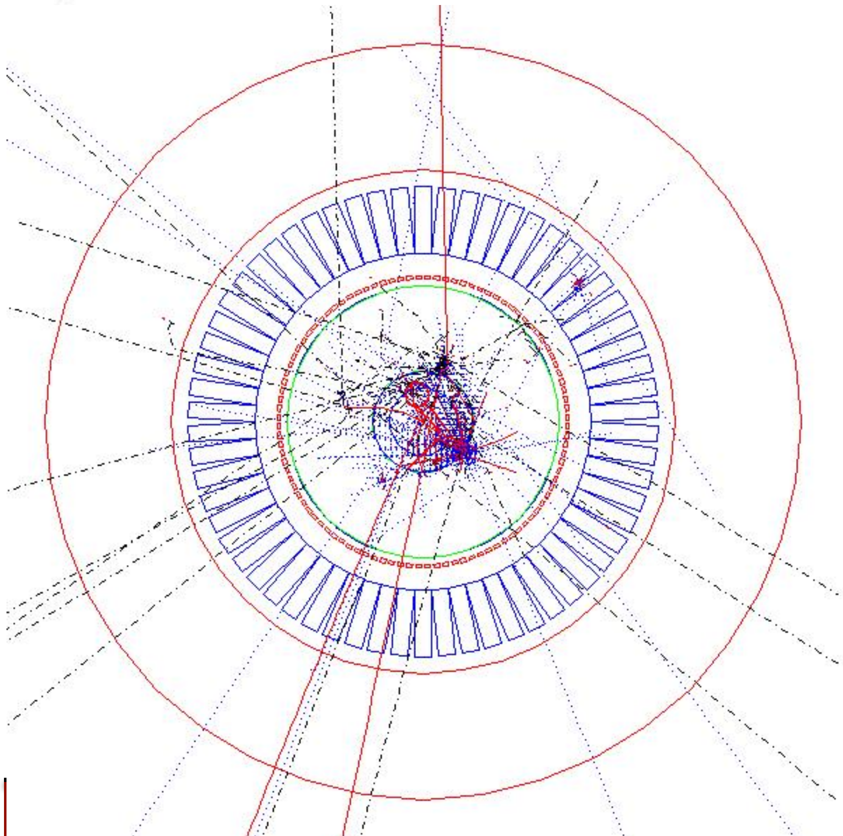
First ideas for a detector concept

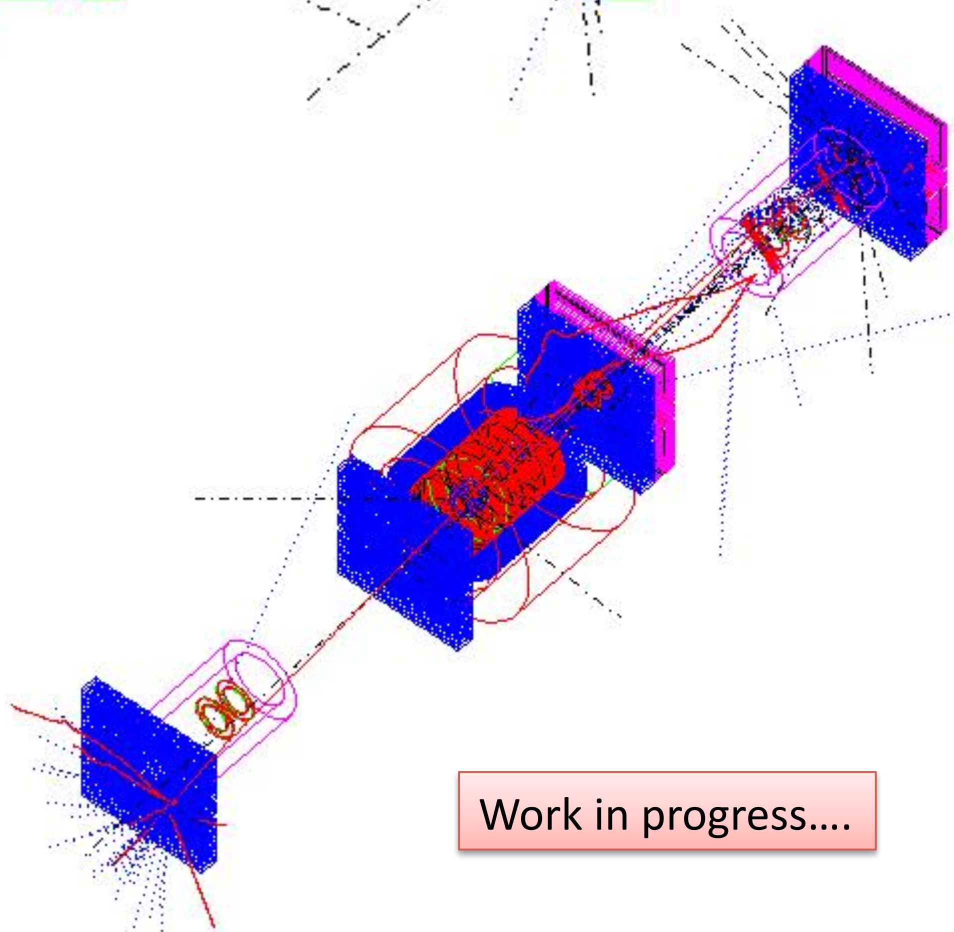


- Dipoles needed to have good forward momentum resolution
  - Solenoid no magnetic field @ r ~ 0
- DIRC, RICH hadron identification → π, K, p
- high-threshold Cerenkov → fast trigger for scattered lepton
- radiation length very critical → low lepton energies

MeRHIC Detector in Geant-3





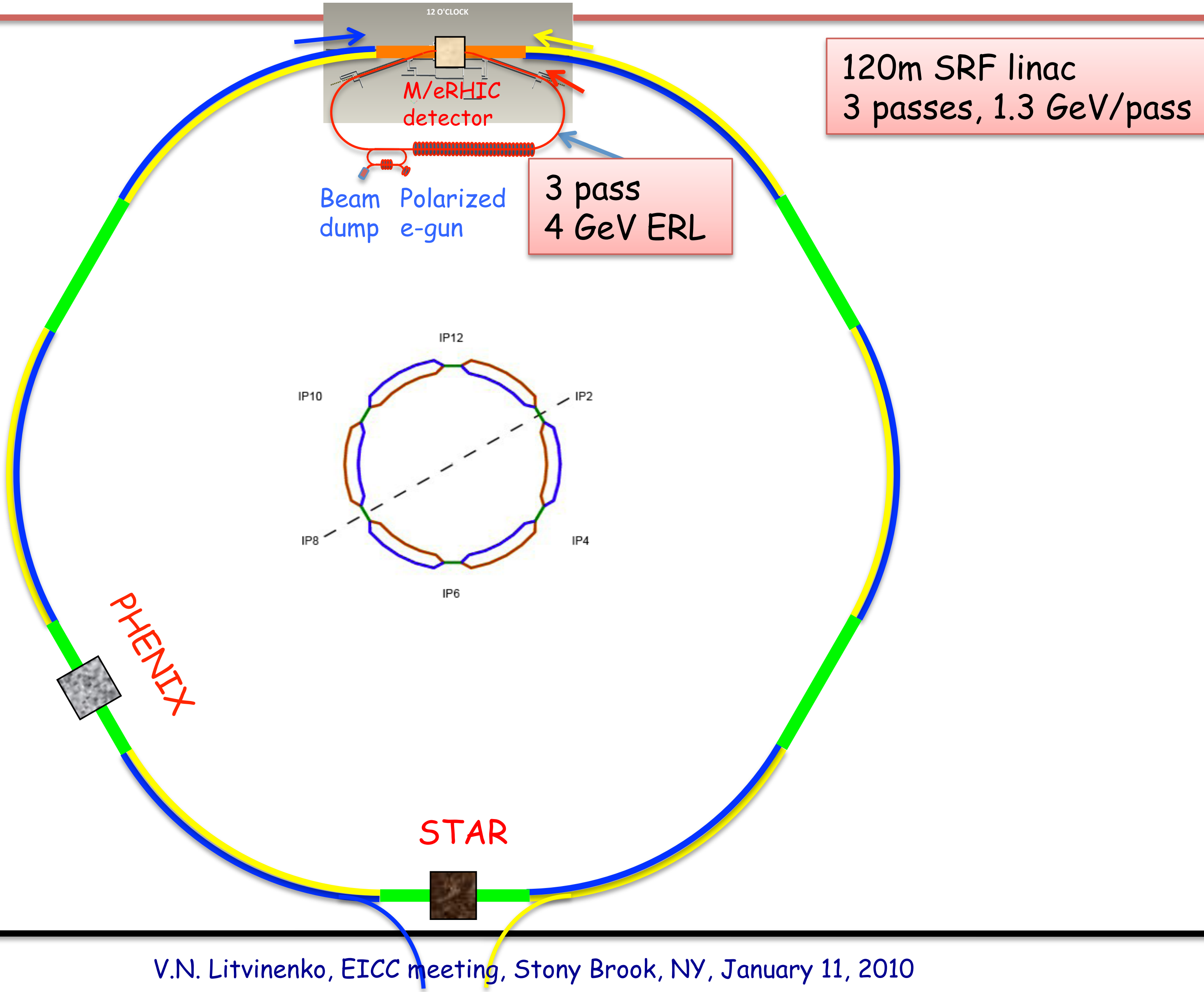


Work in progress….

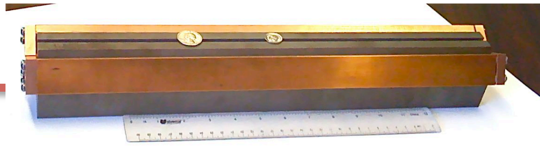
Machine Designs

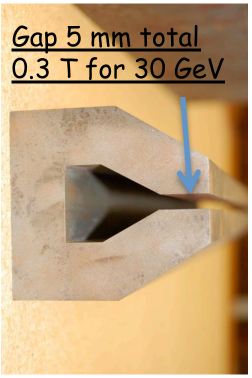
4 GeV e x 250 GeV p – 100 GeV/u Au

MeRHIC

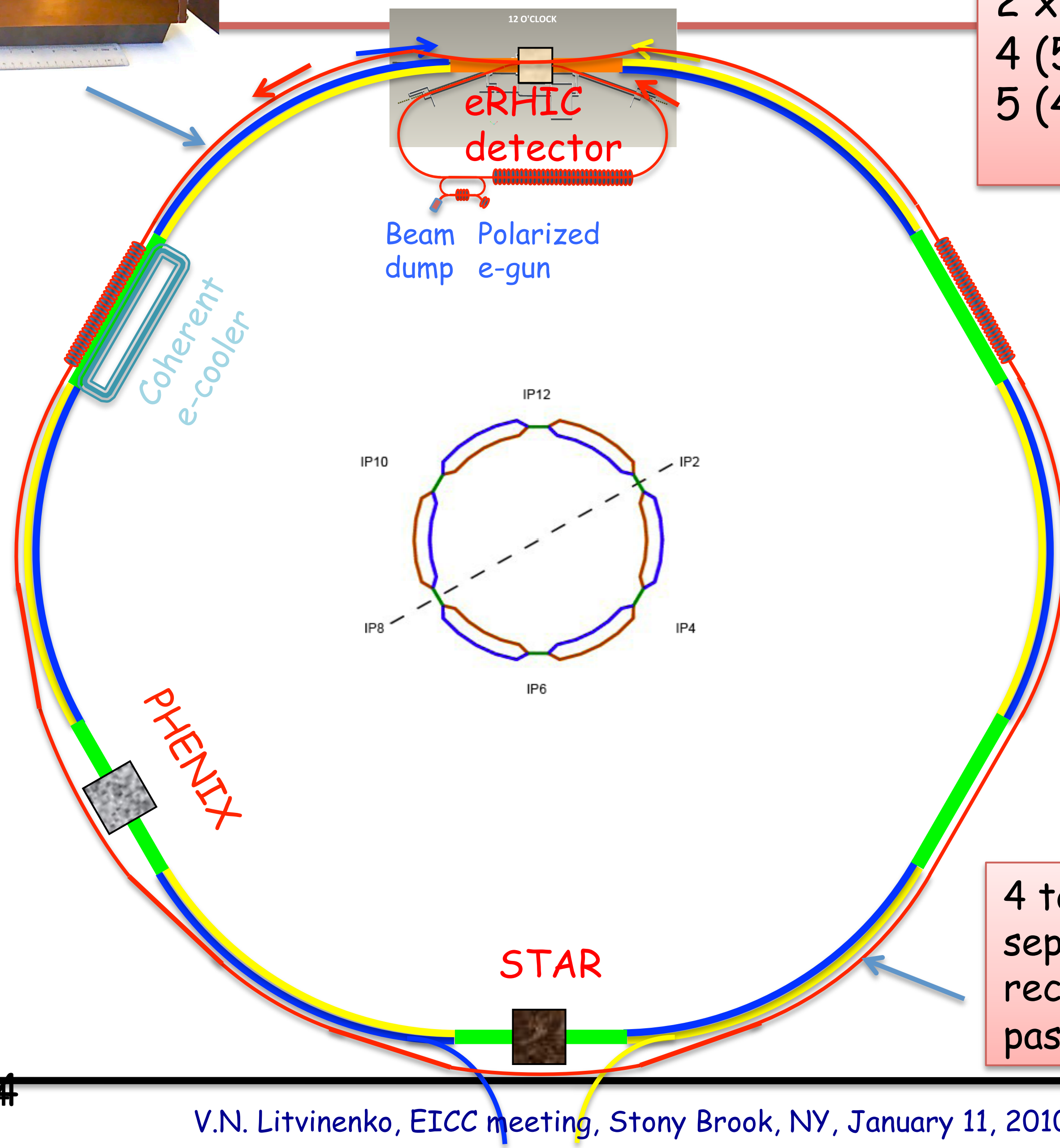


10 to 20 GeV e x 325 GeV p – 130 GeV/u Au
eRHIC

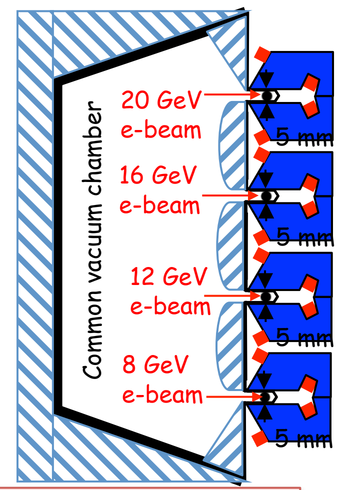




2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes



Possibility of 30 GeV low current operation



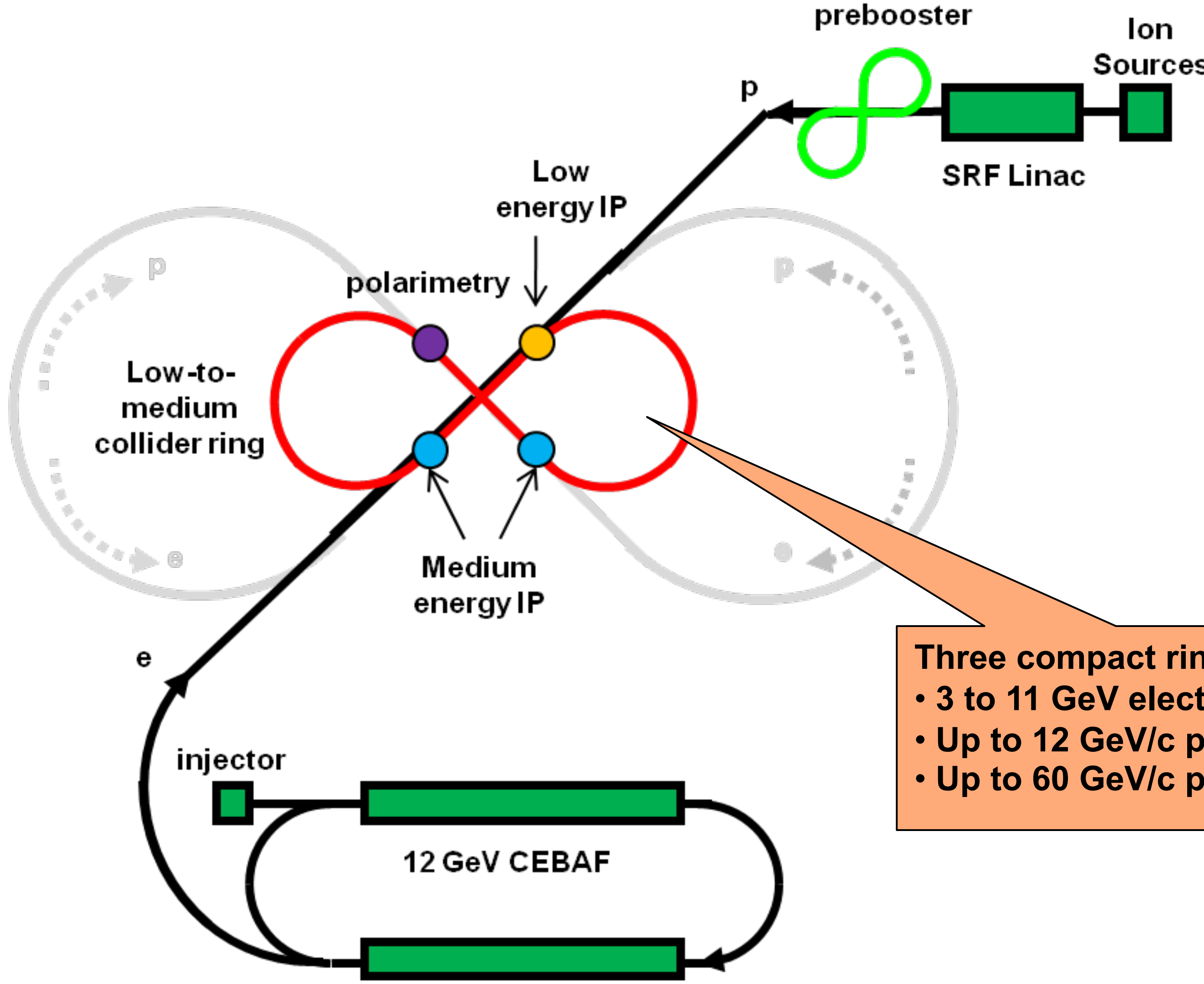
4 to 5 vertically separated recirculating passes

Luminosity in eRHIC

	MeRHIC		eRHIC IR1		eRHIC IR2	
	p /A	e	p /A	e	p /A	e
Energy, GeV	250/100	4	325/130	20	325/130	20
Number of bunches	111	105 nsec	166	74 nsec	166	74 nsec
Bunch intensity (u) , 10^{11}	2.0	0.31	2.0	0.24	2.0	0.24
Bunch charge, nC	32	5	32	4	32	4
Beam current, mA	320	50	420	50	420	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.2	25	1.2	25
Polarization, %	70	80	70	80	70	80
rms bunch length, cm	20	0.2	4.9	0.2	4.9	0.2
β^*, cm	50	50	25	25	5	5
Luminosity, $cm^{-2}s^{-1}$	0.1×10^{33} as is 1×10^{33} with CeC		2.8×10^{33}		1.4×10^{34}	

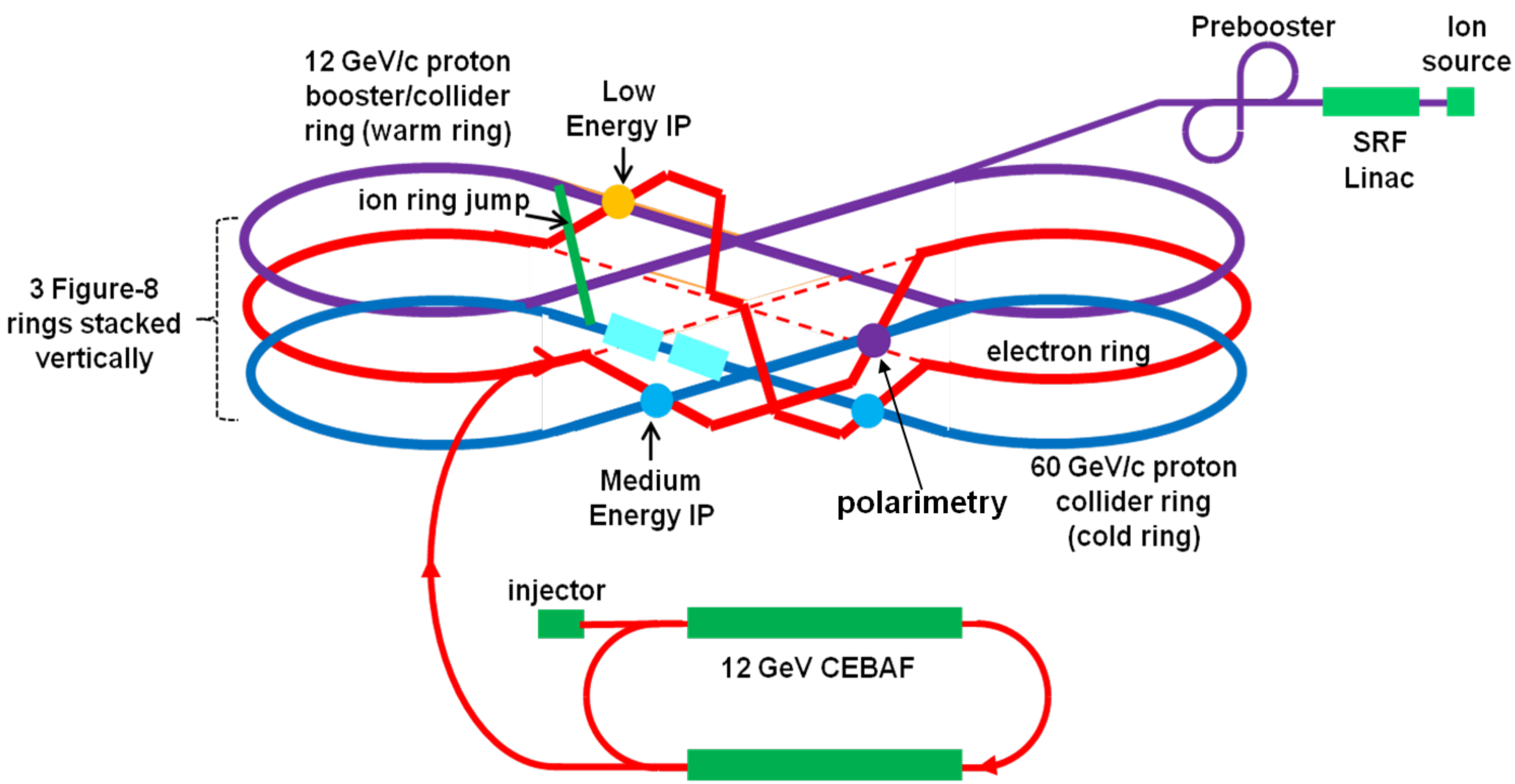
- Luminosity for 30 GeV e-beam operation will be at 20% level:

MEIC: A Medium Energy EIC



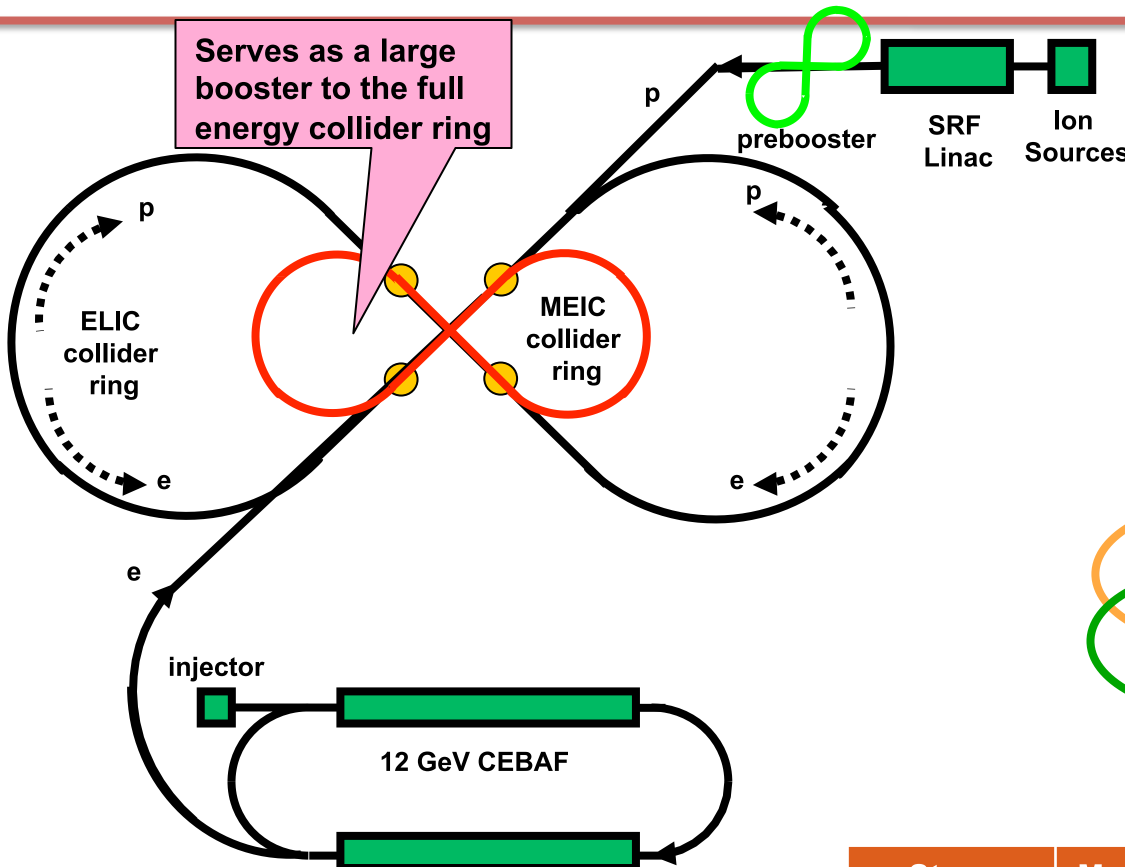
Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)

MEIC: Layout

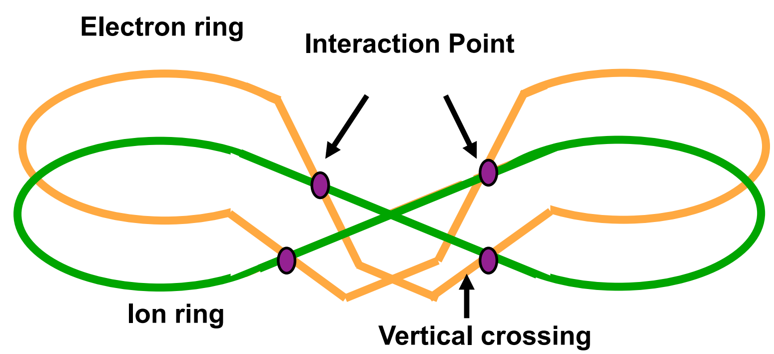


12 GeV/c proton booster/collider ring (warm ring)
Low Energy IP
Prebooster
Ion source
SRF Linac
ion ring jump
3 Figure-8 rings stacked vertically
electron ring
Medium Energy IP
polarimetry
60 GeV/c proton collider ring (cold ring)
injector
12 GeV CEBAF

ELIC: High Energy Upgrade



Circumference	m	1800
Radius	m	140
Width	m	280
Length	m	695
Straight	m	306



Stage	Max. Energy (GeV/c)		Ring Size (m)		Ring Type		IP #
	p	e	p	e	p	e	
Low	12	5 (11)	630		Warm	Warm	1
Medium	60	5 (11)	630		Cold	Warm	2
High	250	10	1800		Cold	Warm	4

ELIC Main Parameters

Beam Energy	GeV	250/10	150/7	60/5	60/3	12/3
Collision freq.	MHz			499		
Particles/bunch	10^{10}	1.1/3.1	0.5/3.25	0.74/2.9	1.1/6	0.47/2.3
Beam current	A	0.9/2.5	0.4/2.6	0.59/2.3	0.86/4.8	0.37/2.7
Energy spread	10^{-3}			~ 1		
RMS bunch length	mm	5	5	5	5	50
Horiz. emit., norm.	µm	0.7/51	0.5/43	0.56/85	0.8/75	0.18/80
Vert. emit. norm.	µm	0.03/2	0.03/2.87	0.11/17	0.8/75	0.18/80
Horizontal beta-star	mm	125	75	25	25	5
Vertical beta-star	mm			5		
Vert. b-b tune shift/IP		0.01/0.1	0.015/.05	0.01/0.03	.015/.08	.015/.013
Laslett tune shift	p-beam	0.1	0.1	0.1	0.054	0.1
Peak lumi/IP, 10^{34}	$cm^{-2}s^{-1}$	11	4.1	1.9	4.0	0.59

High energy Medium energy Low energy

Presented at the last EIC Collaboration Advisory Committee meeting, Nov. 2-3, Jefferson Lab

Summary

Understanding QCD in its full richness needs multiple probes and handles such as spin, energy variation, studies with nuclei

- The Electron Ion Collider will be a unique facility which will greatly enhance our abilities in this regard
- http://web.mit.edu/eicc for EIC information
- *One of the most compelling reason to build the EIC in the US may also be to make sure WV continues to frequent across the Atlantic….*